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RESEARCH MEMORANDUM

INVESTIGATION OF SEVERAL TECHNIQUES FOR IMPROVING ALTITUDE-STARTING LIMITS OF TURBOJET ENGINES

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SUMMARY

The possibilities of altitude combustion blow-out or the need of additional engines for emergency purposes in multi-power-plant aircraft point up the need for rapid, reliable turbojet engines starting at high altitudes. As part of the NACA investigation of altitude starting of turbojet engines the altitude-starting limits of a production engine with an axial-flow compressor and a multiple through-flow combustor were determined. The ignition limits, flame-propagation limits, and to a lesser extent the acceleration limits of the engine were improved to increase the starting limits to relatively high altitude.

Ignition characteristics were improved primarily by replacing the standard induction ignition systems (0.02 joule/spark, 800 sparks/sec) with a high-energy capacitance ignition system (3.7 joules/spark at the spark gap, 7 sparks/sec). The flame-propagation limits of the engine were improved by increasing the size of the cross-fire tubes interconnecting the combustors. An improvement in acceleration characteristics was obtained by using a variable-area exhaust nozzle to increase the jet-nozzle area during engine acceleration. These changes produced an increase in the altitude-starting limit of the engine from 15,000 to 43,000 feet at 0.6 flight Mach number and from sea level to 47,000 feet at 0.8 flight Mach number.

INTRODUCTION

The loss of power from the gas-turbine power plant of a single-engine aircraft as a result of combustor blow-out is a hazardous condition most likely to occur at high altitude during violent maneuvers such as experienced in combat. Also, multiengine aircraft that may be flying with only part of the engines operative to obtain maximum range may in emergency require full power from all the engines. In either the restart following combustor blow-out or the starting of additional engines, the safety of the aircraft and crew may well depend on the ease of restarts and the time required to obtain full engine power. Considerable time is consumed if it becomes necessary to seek a lower altitude or to change flight speed in order to start effectively and to obtain full power from all engines. It is therefore highly desirable to raise the altitude-starting limit of the engine to the maximum altitude operating limit of the aircraft over its flight speed range.

Successful starting of gas-turbine engines with multiple combustors consists of three phases: (1) ignition of one or more of the combustors containing ignition devices, (2) propagation of flame from the ignited combustor or combustors to all the other combustors, and (3) acceleration of the engine from starting to full speed without exceeding the allowable temperature of the engine parts and without encountering compressor surge or stall. Because any one of these factors can limit the altitude-starting limits of the engine, it becomes necessary that the altitude limits of each be extended to the operational ceiling of the engine. Results of fundamental research conducted on the basic processes involved in gas-turbine-engine starting, such as flammability limits, minimum ignition energies, and flame propagation, are reported in references 1 to 7. Application of these results to single combustor apparatus is discussed in references 8 and 9, and the application to full-scale gas-turbine engines is presented in references 10 to 13.

The present investigation was conducted to obtain effective starting of current gas-turbine engines to their maximum altitude operating limits, which in present-day engines at subsonic flight speeds is generally from 50,000 to 60,000 feet. The investigation was conducted in an NACA Lewis laboratory altitude chamber over a range of altitudes from sea level to 57,000 feet at flight Mach numbers from 0.2 to 1.2 with an axial-flow turbojet engine having through-flow can-type combustors. Data are presented to indicate the best configurations and techniques for ignition, flame propagation, and engine acceleration. Included are the effects of spark-gap location, spark-repetition rate, spark energy, and flight Mach number on altitude-ignition limits; the effects of cross-fire-tube diameter and location, fuel volatility, fuel and air temperatures, and type of fuel nozzle on altitude limits of flame propagation; and the effect of jet-nozzle area on altitude-acceleration limits. A portion of these data were reported in a preliminary report (reference 14) covering the early part of this investigation. These data are included herein together with more recent data to provide a complete report of this altitude-starting investigation.

APPARATUS

Engine

The turbojet engine used in this investigation has an axial-flow compressor, eight cylindrical through-flow combustors, and a single-stage turbine. The engine diameter is 43 inches and the individual combustors have maximum diameters of $9\frac{3}{8}$ inches, providing a combustor area equal to nearly 37 percent of the engine frontal area. The ignition system is an induction-coil-type system producing 800 sparks per second of 0.02 joule per spark. Spark plugs are installed in only two of the combustors. Ignition in the other combustors depends on transporting the flame from the combustors having spark plugs to the remainder of the combustors through cross-fire tubes interconnecting the combustors. The cross-fire tubes are 7/8 inch in diameter.

The engine has a nominal thrust rating of 5000 pounds, and its performance and starting characteristics are typical of present-day axial-flow compressor, tubular-combustor turbojet engines.

Installation

The engine was mounted in an altitude chamber 10 feet in diameter and 60 feet long, schematically shown in figure 1. Screens and air-straightening vanes are installed upstream of the test section to provide a flat velocity profile to the engine inlet. The forward bulkhead separates the inlet air from the exhaust section and provides a means of maintaining a pressure difference across the engine. The rear bulkhead serves as a radiation shield and prevents the recirculation of exhaust gases about the engine. The exhaust gas from the jet nozzle was discharged into an exhaust diffuser and thence through coolers, control valves, and exhausters to atmosphere.

Instrumentation

Pressure and temperature instrumentation was installed before and after each component of the engine as shown in figure 2. The instrumentation used in this investigation was as follows: At station 1, eight total-pressure probes and eight thermocouples on equal areas were used in setting engine ram pressures and temperature. At station 5, two wall static-pressure orifices were used to obtain combustor static pressures. At station 6, eight probes (one in each combustor) measured total pressure and temperature at the combustor outlet; the thermocouples were used to determine the sequence of ignition of the combustors. At station 8, four thermocouples were averaged and used as limiting temperature measurements during the engine-acceleration investigation. The exhaust pressure or altitude settings were made with two static-pressure tubes attached to the lip of the jet nozzle. Also, in each of the cross-fire tubes joining combustors 1, 2, and 3, two total-pressure tubes were installed pointing in opposite directions along the cross-fire-tube axis. These pressure measurements were used to determine the direction of flow in the cross-fire tubes during the investigation of flame-propagation limits.

Experimental Variables

The variables investigated during this altitude-starting investigation are described in table I.

Fuel and fuel systems. - The fuel used throughout most of this investigation was a low-volatility experimental fuel having a 1 pound per square inch Reid vapor pressure. In order to determine the effects of fuel volatility on ignition and flame-propagation limits, a fuel with a Reid vapor pressure of 6.2 pounds per square inch was used. The fuel inspection data for these two fuels are tabulated in table II.

A schematic diagram of the fuel system used is shown in figure 3. The cooler in the bypass system permitted adjustment of fuel temperatures. A pressure-regulating valve upstream of the throttle replaced the standard engine fuel controls so as to provide more sensitive control of fuel flows at the low fuel rates required for starting. Fuel temperature was measured by an iron-constantan thermocouple in the fuel line downstream of the cooler and checked under starting flow conditions by another thermocouple mounted just upstream of the fuel distributor. Although duplex fuel nozzles were standard equipment for the engine, a set of variable-area fuel nozzles and a fuel distributor were used during the early phases of the investigation in an attempt to improve the fuel atomization and to provide equal fuel distribution to the combustors. Even with this system the results were often difficult to reproduce when cold fuel was used. This difficulty was attributed to excessive friction of moving parts of the nozzle; therefore, the variable-area fuel nozzles were replaced with small simplex fuel nozzles (5 gal/hr tips) which produced more consistent spray patterns and atomization and improved the reproducibility of the starting data. The simplex fuel nozzles were used throughout the high-spark-energy phase of the investigation. The fuel nozzles used in each phase of the investigation are indicated in table I and on each figure presenting research results.

Ignition systems. - The standard engine ignition system, schematically represented in figure 4(a), was an induction-type ignition source which discharged 800 sparks per second at approximately 0.02 joule per spark through A.C. F-67 spark plugs. In order to determine the effects of spark energy and spark-repetition rate on ignition limits, the high-energy capacitance-type ignition system shown diagrammatically in figure 4(b) was constructed. For this investigation, the voltage indicated by the peak voltmeter was held constant at 10,000 volts. Spark plugs used with this ignition system were of two types (1) standard A.C. F-19 spark plugs, and (2) opposed spark plugs. The opposed spark plugs consisted of two electrodes spaced 140° apart and installed so as to provide a 0.11-inch gap located on the center line of the combustor 5 inches downstream of the fuel-nozzle tip. Originally the electrodes were constructed from 3/16-inch heavy wall stainless-steel tubing, but these were later replaced with 3/16-inch Inconel rod to retard erosion and the consequent widening of the spark gap.

For comparative purposes, a second capacitance-type ignition system, which was being developed commercially, was investigated. This unit was operated at four spark-energy levels at 4 to 7 sparks per second and at a spark potential of 1000 volts. The spark plugs used with this system were A.C. F-19 plugs.

Spark-energy measurements. - The values for spark energy released and repetition rate for both the induction and low-voltage commercial systems were supplied by the manufacturer. Determination of spark energy for the high-voltage capacitance system was initially calculated by using the known capacitance of the condensers and the voltage as indicated by the peak voltmeter shown in the circuit diagram of figure 4(b). However, these measurements were found to be in serious error, because the condensers apparently did not completely discharge, and there were appreciable losses in the ignition harnesses and connectors. In order to determine the energy dissipated at the spark gap, a calorimeter was developed that may provide a standard means of measuring spark energy at the spark gap. A schematic diagram of the calorimeter is presented in figure 5. Because the measurement of electric surges of short duration, such as a condenser discharge into a spark gap, was difficult to measure by voltage and amperage, a comparison was made of the heat output of the spark discharge with that of a heater coil where the electric power inputs did not surge and were simple to measure. The spark was contained in a well-insulated container of extremely low heat capacity (fig. 5(a)), where the heat output of the spark was indicated by a resistance thermometer. The indication of the resistance thermometer was duplicated by the heat output of a heater coil where the power input was measured by a wattmeter (fig. 5(b)), thus determining the power input of the spark from the measured power input to the heater coil. The heater coil was made of Manganin wire to reduce the variation of power input that would accompany any change of coil resistance caused by a temperature change. In order to obtain more accurate spark-energy measurements, especially at low energy levels, the heat capacity of the calorimeter was kept to a low value. Thus instead of using standard plugs in the calorimeter, 1/2-inch lengths of the center electrodes were connected to the ignition leads so as to form a uniform gap of 0.11 inch. All measurements made by the calorimeter were obtained at approximately sea-level pressure and temperature.

PROCEDURE

Ignition

As was shown in the tabulation of experimental variables, two procedures were used in obtaining engine altitude-ignition limits. Primarily these procedures were associated with the method of throttle manipulation during an attempt to obtain ignition.

Variable-throttle ignition. - With variable-throttle ignition, the altitude pressure was set in the exhaust portion of the altitude chamber, and compressor-inlet pressure and temperature were adjusted to simulate a particular flight speed assuming a 100-percent ram-pressure recovery to the engine. The fuel circulating through the fuel cooler was adjusted to equal the compressor-inlet-air temperature. The engine windmilling speed was stabilized and the engine windmilled freely at the desired compressor-inlet temperature for approximately 2 minutes to allow the temperature of engine parts to stabilize. Then the ignition was switched on and the throttle slowly opened until ignition was obtained or until a fuel flow sufficient to ensure a mixture well above stochiometric in the combustion zone was obtained, after which the throttle was slowly closed. The entire throttle manipulation was timed in order to complete the cycle in 30 seconds, at which time the ignition was automatically cut off. Although this method was simple and gave reasonably reproducible results, it was not particularly adaptable to an aircraft automatic control system, in which it would be desirable to have a simple schedule of fixed flow rates for each flight condition.

Fixed-throttle ignition. - In order to simulate more accurately starting with an automatic control system, near optimum fuel flow was determined for altitudes above 35,000 feet. These fuel flows were then fixed for each flight condition as part of the starting procedure. The fixed-throttle starting procedure consisted of establishing altitude and ram pressures and engine-inlet air and fuel temperatures as before. The fuel was then set at the predetermined fuel flow and the ignition turned on for 30 seconds. With each starting system, several attempts were made to obtain ignition at each simulated flight condition. The flight condition was designated as an ignitable flight condition only if ignition was established for each of the several attempts to obtain ignition. The altitude increments investigated varied from 2000 to 5000 feet.

Flame Propagation

The flame-propagation phase of the investigation was carried out by going through a normal ignition procedure and noting the sequence of flame propagation on the gages connected to the thermocouples in each combustor exit. Unless all burners were ignited within 30 seconds, flame propagation was considered incomplete.

Acceleration

The time required for acceleration was determined by going through a normal starting procedure, completely igniting all burners, and then manipulating the throttle to hold limiting tail-pipe temperature as near as possible. The acceleration time was taken as the time from the instant flame propagation was complete to all burners until 75 percent of rated speed was reached. Engine speed was limited to about 75 percent of rated speed by the flow rate of the simplex fuel nozzles used during the major portion of this investigation.

RESULTS AND DISCUSSION

As pointed out earlier, a complete start of a multicombustor turbojet engine is composed of three distinct phases, namely: (1) establishing ignition in the combustors having ignition sources such as spark plugs, (2) propagation of flame from the ignited combustors to the remaining combustors through the interconnecting flame tubes, and (3) acceleration from the starting engine speed to a useful speed. The altitude limits for each phase of the altitude start are shown in figure 6 for the engine in the standard configuration, except that variable-area fuel nozzles were used in place of the standard duplex nozzles. Acceleration of the rotor in an arbitrarily selected maximum time of 1 minute restricted altitude starting to 14,000 feet at a flight Mach number of 0.20. As flight Mach number was increased, the starting limit increased to 29,000 feet at a flight Mach number of 0.41. At flight Mach numbers greater than 0.41 failure to obtain ignition imposed the limiting altitude at which a start could be made and reversed the trend exhibited by the acceleration limit; until at a flight Mach number of 0.8, starting was limited to sea-level conditions. The rapid decay of the altitude-ignition limit as flight Mach number increased was attributed to the increased air velocity through the combustor which accompanied an increased windmilling engine speed. The flame-propagation limit was high enough (30,000 ft) to exceed either the ignition or acceleration limits at all flight Mach numbers and therefore did not restrict engine starting. Nevertheless, if the altitude-starting limit is to be raised to an altitude of about 50,000 feet, which is near the altitude operating limit of most current engines, then all three phases of the engine start must be improved.

Altitude Ignition

Such factors as combustor configuration, operational conditions, and fuel properties, which affect ignition in gas-turbine engines, have been individually investigated (references 1 to 13). From these investigations the following criteria for good combustor ignition characteristics have evolved: (1) high pressure and temperature and low velocity in the ignition zone; (2) a fuel-vapor to air mixture near stoichiometric in the spark-plug gap, which requires both a relatively volatile and well-atomized fuel; (3) absence in the ignition zone of large quantities of liquid fuel that tend to quench any initiated combustion; (4) a well-formed spray pattern over the starting speed range and under the lowest fuel temperatures likely to be encountered; and (5) sufficient spark energy for ignition at the existing pressure, temperature, and velocity conditions. The application of these criteria to improvement of the altitude-ignition limit of the engine whose altitude-starting limit is shown in figure 6 is described in the following paragraphs.

Effect of fuel volatility. - In view of the need of vaporized fuel for ignition, it would be expected that when fuel volatility is increased, with the consequent increase in evaporation rate, the fuel-air mixture would generally be less difficult to ignite. The improvement in altitude-ignition limit when the fuel volatility was increased from 1.0 to 6.2 pounds per square inch Reid vapor pressure is shown in figure 7. At a flight Mach number of 0.4, the increased fuel volatility increased the altitude limit by 15,000 feet. At higher flight Mach numbers the improvement was less significant.

A highly volatile fuel, however, leads to additional problems in flight; for unless the fuel tanks are pressurized, a large percentage of the fuel can be lost by boiling off the more volatile fuel fractions at the low pressures existing at altitude. This loss not only reduces aircraft range, but the advantage of the more volatile fuel is lost as the more volatile fractions boil away. For this reason there is at present a trend towards less volatile fuels for turbojet engines; and in order to cover the more adverse conditions for starting, the 1 pound per square inch Reid vapor pressure fuel was used throughout the remainder of the investigation.

Effect of fuel and air temperatures. - Because the rate of evaporation of fuels decreases with decreasing temperature, a reduction in fuel and air temperatures would be expected to lower altitude-ignition limits. The effects of independently varying fuel and engine inlet-air temperatures at a flight Mach number of 0.6 are shown in figure 8. As either fuel or air temperature was decreased, there was a progressive decrease in altitude-ignition limit. A reduction in fuel temperature from 30° to -2° F generally reduced the altitude-ignition limit less than 5000 feet; but when the fuel temperature was reduced to -30° F, a very abrupt lowering of the altitude limit was found with engine inlet-air temperature lower than 0° F. This abrupt reduction in altitude limit was first believed to result from a deterioration of atomization as the fuel viscosity increased. The fuel viscosity increase, in turn, resulted from the lowered heat transfer from the fuel to the fuel nozzle at the lower air temperatures. The higher viscosity would tend to reduce the energy in the fluid stream available for atomization; furthermore, the cold fuel nozzle might cause binding of the moving parts. A subsequent visual examination of the spray cone on the flow bench with cold fuel, however, did not reveal any differences in spray pattern. Additional evidence that the nozzle was operating satisfactorily was found in that at sea-level static conditions ignition was obtained with fuel and air temperatures as low as -50° F (the limit of the refrigeration system for the air flows required). It is concluded that fuel-spray pattern and nozzle binding were not responsible for the abrupt drop in ignition limit. In all probability, ignition was of a borderline nature and at the lower fuel and air temperatures and resultant lower vaporization rates, the high air velocities through the combustor at the 0.6 flight Mach number swept the vaporized fuel from the combustor before an ignitable fuel-vapor and air mixture could be established. At sea-level static conditions, the longer residence time (lower air velocity in the combustor at engine cranking speeds) allowed the establishment of a combustible fuel-vapor and air mixture which is ignitable at the existing pressure level in the combustor.

Effect of spark-gap immersion. - Injection of liquid fuel in the form of a hollow cone into the engine combustor results in a very stratified fuel-air mixture. If the spark electrodes are directly in the liquid fuel stream, ignition is difficult because of the quenching action of the fuel. If the spark electrodes are too far from the fuel-spray cone, the mixture may be too lean for ignition. In order to explore this effect, the spark plug was moved both fore and aft of its standard location. In the nominally $7\frac{1}{2}$-inch-diameter combustor liner, the spark gap was 2 inches downstream of the fuel-nozzle tip and penetrated into the liner far enough to be just inside the nominal fuel-spray cone of 120°. With the spark plug moved farther upstream into the combustor dome and with the spark gap outside the fuel-spray cone, the altitude ignition was much poorer than in the standard location. When the spark plug was moved 2 inches farther downstream, starting was better than it was with the dome location but not as good as with the standard location. At the standard location, the spark gap was progressively inserted radially into the combustor until the combustor center line was reached (reference 14). Each increased increment of immersion appreciably increased the altitude-ignition limits. In the present investigation the spark electrodes were lengthened to move the spark gap to the center line of the combustor, and the improvement in altitude-ignition limit is shown in figure 9. At flight Mach numbers of 0.4 and below, there was no improvement in altitude limits; but at the higher flight Mach numbers, appreciable improvements were obtained. At 0.8 flight Mach number, moving the spark gap to the center line of the combustor raised the altitude-ignition limit from about sea-level conditions to 20,000 feet.

This improvement may indicate that at the low flight Mach numbers fuel vapor was present in sufficient quantities at both locations because of the relatively low air velocities in the combustor. At the higher flight Mach numbers the fuel vapor was swept away from the spark gap by the higher combustion-chamber velocities at the standard location; whereas, it was afforded a more sheltered region for fuel-vapor accumulations and ignition at the center location.

Effect of spark energy. - It would be expected that deficiencies in atomization, vaporization, and in fuel-vapor and air mixture, or excessive velocities or low temperatures could be partially overcome by increased spark energy. The high-energy capacitance ignition system shown in figure 4(b) was therefore constructed to investigate the effects of spark energy on altitude ignition. The capacitance-type ignition unit allowed an increase of several hundred times the energy per spark obtainable from the standard induction-type ignition unit. Obviously, to construct an induction-type unit to produce the same energy per spark would require a unit many times the size and weight of the capacitance system.

In the early phase of the high-energy ignition investigation, results were quite erratic. In order to improve reproducibility, the variable-area fuel nozzles were replaced with 5-gallons-per-hour-tip simplex fuel nozzles, as it was thought that the moving parts in the variable-area nozzles might be sticking under the cold altitude-starting conditions. Some difficulty was also experienced with arcing in the standard spark-plug cable connectors. Two spark plugs containing only center electrodes were then installed in each of the two igniting combustors. They were placed about 140° apart in the combustor shell, so that the electrodes came together in the center of the combustor to form the spark gap. The "hot" ignition lead was then soldered to the center electrode of one plug, and the other electrode was grounded. The soldered joint was covered with Saran tubing filled with a silicone compound to prevent corona losses. These changes improved the reproducibility. With this configuration, the spark-energy output required for ignition as altitude was increased is shown in figure 10 for a constant flight Mach number of 0.6. The altitude-ignition limit increased rapidly from 35,000 feet at 0.23 joule per spark to 45,000 feet at 0.5 joule per spark. Approximately 1.4 joules per spark appeared necessary to obtain ignition at an altitude of 50,000 feet. Any further altitude increase appeared quite difficult to realize, for it was not possible to obtain ignition at 55,000 feet with the highest available spark energy (about 3.7 j).

For comparison, the altitude-ignition limits of the standard induction-type ignition system with both the standard and fully immersed spark-gap locations are shown in figure 9 to be 15,000 and 25,000 feet, respectively. This comparison is of particular interest, inasmuch as the standard induction system with 800 sparks per second and 0.02 joule per spark or 16 watts ($800 \times 0.02 = 16$ j/sec = 16 w) provided ignition to only 25,000 feet as compared with 50,000 feet for about 1.4 watts from the capacitance ignition system. This comparison indicates the possibility of a 25,000-foot improvement in ignition limit, if the low spark energy were increased at the expense of the high repetition rate.

<u>Effect of spark-repetition rate on power required for ignition</u>. - The effect of spark-repetition rate on the spark energy required to provide ignition at an altitude of 50,000 feet at a flight Mach number of 0.6 is shown in figure 11(a). At a spark-repetition rate of 1 spark per second these data indicate that 2.14 joules per spark are required to produce ignition. However, the large increments of spark energy (1.03 to 2.14 j/spark) imposed by the condensers built into the high-energy ignition system did not permit accurate determination of the energy

required for ignition. Extrapolation by several different methods showed that ignition could be obtained at the 50,000-foot 0.6-Mach-number condition with approximately 1.4 joules per spark at 1 spark per second (fig. 11(a)). These values are also in agreement with the data of figure 10. When spark-repetition rate was increased to 188 sparks per second, the energy required for ignition decreased to 0.34 joules per spark. The predominant effect of spark energy is evident from the 188:1 increase in spark-repetition rate required to offset a 4:1 decrease in spark energy.

The advantage of low repetition rate is more forcibly demonstrated in terms of the power required for ignition (fig. 11(b)). Of course, power requirements should be kept low to keep the battery drain to a minimum. At a spark-repetition rate of 188 sparks per second, the power required to establish ignition was 62 watts, whereas only 1.4 watts were required at 1 spark per second. It is therefore apparent that use of a combination of high spark energy and low repetition rate will produce ignition for the minimum expenditure of power.

The advantage of the high energy - low repetition rate combination is undoubtedly a result of the high concentration of energy, which can locally vaporize fuel, overcome the disadvantage of nonideal fuel-vapor and air mixtures, and establish a sufficiently strong flame front to propagate to all parts of the burner.

Comparison of performance of two high-energy ignition units. - The advantage of high-energy - low spark-repetition-rate ignition units has been shown. Obviously there are many details of design that can be varied. In addition to the NACA-designed high-energy system, a unit being developed commercially was made available to the NACA; and the performance of these two units was compared. The commercial development unit used a low-energy 15,000-volt spark to ionize the spark gap, and after the gap was ionized the high-energy spark was discharged at about 1000 volts. Several condensers which were available for this unit allowed spark-discharge energies from 1.24 to 4.75 joules per spark. The sparking rate was controlled by a sealed spark gap that provided approximately 7 sparks per second and discharged through a standard A.C. F-19 spark plug. The 10,000-volt NACA unit (schematically shown in fig. 4(b)) was also adjusted to produce 7 sparks per second but was discharged through the 3/16-inch-diameter electrodes with the spark gap located at the center of the combustor. A comparison of the performance of the two units is presented in figure 12. At the lower spark energy, 1.24 joules per spark, of the unit being developed for commercial purposes, ignition was possible to 42,500 feet; whereas the 10,000-volt or high-voltage unit provided ignition to 50,000 feet with the same spark energy. The advantage of the high-voltage system over the commercial system is attributed to the center-of-combustor spark-gap location. However, at the higher spark energies, the commercial system produced ignition limits equal and possibly superior to those of the high-voltage systems.

Because of the effects of spark-gap location and spark-electrode size, a direct comparison of the two ignition systems is impossible. However, with either system with spark energies of about 3.7 joules per spark and at 7 sparks per second, ignition was possible to 53,000 feet under the quite adverse conditions imposed by use of a cold low volatile fuel and a relatively high flight Mach number.

It is of interest that early in the program, altitude ignition was obtained to an altitude of 60,000 feet at a flight Mach number of 0.6 with 3.7 joules per spark at 7 sparks per second. The 60,000-foot ignition was obtained with 3/16-inch-diameter heavy wall Inconel tubing as the electrodes. The rapid erosion of the tubing greatly reduced system reliability, and the tubing was replaced with 3/16-inch rod, which resulted in the lowering of the ignition limit to 53,000 feet.

Effect of flight Mach number. - It has been shown that with the standard-engine low-energy spark system the effect of increasing flight Mach number was to decrease rapidly the altitude at which ignition could be obtained, and that at 0.8 flight Mach number ignition was not possible except at sea-level conditions. Moving the spark gap to the center of the combustor raised the ignition limit from sea level to 20,000 feet. The effect of flight Mach number with the high-energy system (10,000 v, 3.7 j/spark, 7 sparks/sec) is shown in figure 13. The characteristic decrease in altitude-ignition limit is again apparent as flight Mach number was increased from 0.4 to 1.0. At flight Mach number of 0.4, 0.6, 0.8 and 1.0 the corresponding altitude limits were 55,000, 53,000, 47,000 and 46,000 feet respectively. As flight Mach number was increased from 1.0 to 1.2, the altitude-ignition limit rose rapidly from 46,000 to 56,000 feet. This improvement was a result of rapidly increasing combustor pressure and temperature, which overcame the adverse effects of high air velocities and high turbulence.

The reversal in trend of the ignition limit with increasing flight Mach number is important, for it shows that the high subsonic interceptors and bombers will have the greatest difficulty obtaining ignition when there is combustor blow-out or when additional engines are to be started to increase flight speed. On the other hand, it is apparent that engines of this type will be more easily ignited at supersonic flight speeds than at subsonic speeds.

Effect of ignition harness and connectors. - Data thus far considered have shown that the most efficient system for providing ignition to altitudes up to 50,000 feet would have a low spark-repetition rate and a high spark energy of 3 to 5 joules per spark in the spark gap. In order to provide the required spark energy at the spark gap, system losses must be carefully considered. Of particular interest are the large losses inherent in the ignition harness and its connectors. As previously mentioned, the ignition harness supplied with the engine proved unsatisfactory when high-energy capacitor discharges were introduced into the harness because of losses encountered in both the connectors and the cable. The losses in the connectors were a result of high electric resistance of the parts and the presence of corona at high altitude. The connectors were filled with a silicone compound to eliminate air spaces around the high-voltage electric conductors and thus prevent corona. But the design of the connectors was not conducive to easy purging of the air spaces, and air pockets frequently existed. Thus corona losses reduced the spark energy at the spark gap; and in some cases the silicone compound apparently decomposed and short-circuited the spark plug, which prevented further discharges at the spark gap. The shielded cable also introduced large losses as a result of high electric resistance. In order to determine the magnitude of the resistance losses, a standard 3-foot cable without connectors with a resistance of approximately 1.2 ohms and a special 3-foot cable of 0.007 ohm were compared by means of the calorimeter shown in figure 5. Power was supplied by a capacitor charged to 1000 volts and discharged once each second. The energy measured at the spark gap with the standard cable was 1.2 joules per spark, while 4.8 joules per spark were obtained when the special cable was used. Additional losses would have occurred if the standard connectors had been used, because the spring contactors on the cigarette tips each have a resistance of approximately 0.2 ohm. Thus the spark energy available at the spark gap may be more than quadrupled if the standard ignition harness is replaced by harness of low electric resistance.

Flame Propagation

After ignition is established in one or more combustors containing ignition devices, the second phase of a successful start is to obtain propagation of flame from the ignited to unignited combustors through the interconnecting cross-fire tubes.

In order to gain a better understanding of the flow conditions involved in flame propagation, two cross-fire tubes in one combustor were instrumented as shown by the sketch in figure 14. The differential of two total-pressure probes located in each tube was traced on an oscillograph so that a positive value represented flow from the ignited to the unignited combustor, while negative values indicated the reverse. A tracing of the oscillograph data of an attempted start at 45,000 feet and a flight Mach number of 0.6 is shown in figure 14. The initial outlet temperature was the same for each burner, but the traces have been separated for clarity. Because the spark plug was located in combustor 2, the first indication of temperature rise occurred in combustor 2 and at approximately 0.9 second after energizing the ignition system. At the same time a velocity in cross-fire tubes A and B from combustor 2 into combustors 1 and 3, respectively, was indicated on the oscillograph trace. After 8 seconds had elapsed, the discharge temperature from combustor 2 and the velocities in both cross-fire tubes had gradually increased to considerably higher values. It is therefore evident that the flow through the cross-fire tubes is established as a result of ignition in a particular combustor which gives a small rise in pressure level in the ignited combustor. The pressure differential between the ignited combustors and unignited combustors results in the flow of ignited gases through the cross-fire tubes to ignite the adjacent combustors.

Referring again to figure 14, combustor 1 ignited after approximately 9 seconds, at which time the velocity in tube B again increased; but because the pressure was nearly equalized between combustors 1 and 2, the velocity in cross-fire tube A decreased essentially to zero. After 18 seconds combustor 3 ignited, and the velocity through cross-fire tube B was also reduced to nearly zero. If the traces had been continued for several minutes to allow the temperatures to equalize in all three combustors, the velocity through cross-fire tubes A and B would have been entirely eliminated.

The gases flowing through the cross-fire tubes obviously must be capable of supporting combustion, and the success of the flame-propagation process is therefore subject to the mixture and quenching variable previously discussed in connection with ignition. It has also been shown in laboratory tests that the flammability limits of a mixture are greatly influenced by the quenching action of cold walls of small tubes (reference 7). Because the cross-fire tubes were only 7/8 inch in diameter in the engine used in this investigation, and the altitude propagation limited to only 30,000 feet (fig. 6), cross-fire-tube diameter was investigated as a means of raising the altitude-propagation limits of the engine.

Effect of cross-fire-tube diameter. - The cross-fire-tube diameters were increased from the standard engine 7/8-inch diameter to $1\frac{3}{8}$ and then to 2 inches in diameter. The altitude flame-propagation limits for these configurations are shown in figure 15 for a range of flight Mach numbers. The increase in diameter from 7/8 to $1\frac{3}{8}$ inches increased the altitude limits at flight Mach numbers of 0.4 to 0.8 from 30,000 to 45,000 feet. Increasing the cross-fire-tube diameter to 2 inches resulted in successful propagation to the maximum altitude at which ignition was obtainable, 55,000 feet. These propagation limits were obtained, however, by considerable throttle manipulation with flame propagation usually being obtained by reducing fuel flow momentarily to a nearly closed throttle condition. Such a manipulation does not lend itself to automatic starting systems, however, and an additional investigation should be made to determine the propagation limits with large cross-fire tubes and the same fuel flows as required for ignition.

Effect of cross-fire-tube location. - Cross-fire-tube diameter has been shown to have a major effect on altitude-propagation limits. It would be expected, also, that the location of the cross-fire tubes with respect to fuel-spray path and combustor flame front could also be critical. The results of an investigation of axial location of the cross-fire tube is shown in figure 16. As the 2-inch-diameter cross-fire tube was moved from the standard engine cross-fire-tube location (5 in. downstream of the fuel-nozzle tip) to 7.5 and 10 inches downstream of the fuel-nozzle tip, there was a progressive drop in propagation limits from about 55,000 to an average altitude of 45,000 feet. In an earlier investigation the cross-fire tubes had been moved up into the combustor dome, where it was found that flame propagation was impossible at any altitude apparently because of a complete absence of flame near the liner wall in this region. In the $9\frac{3}{8}$-inch combustor under investigation and with a fuel nozzle having a nominal fuel-spray cone angle of 120°, it is concluded that the 5-inch location is near optimum for high-altitude propagation.

Effect of fuel atomization and fuel volatility. - The requirement of a near stoichiometric fuel-vapor and air mixture with a minimum of unvaporized fuel for rapid intense flame propagation points to the importance of fuel volatility and atomization as probable factors in the flame-propagation altitude limits. The effect of fuel volatility is shown in figure 17, where the increase in Reid vapor pressure from 1.0 to 6.2 pounds per square inch increased the propagation limit by about 5000 feet when the 7/8-inch-diameter cross-fire tubes and duplex fuel nozzles were used. The effect of atomization was qualitatively investigated by comparing propagation limits with duplex fuel nozzles, variable-area fuel nozzles, and 5-gallons-per-hour-tip simplex fuel nozzles (fig. 18). The difference in propagation limit was small with the different nozzles, and in no case was there a difference in flame-propagation limit greater than 5000 feet.

The primary factors in providing a reliable high-altitude flame-propagation system therefore appear to be the use of large-diameter cross-fire tubes, which undoubtedly should be as short as possible to keep quenching effects to a minimum, and the proper location of the cross-fire tubes with respect to the fuel-spray pattern and the flame front.

Engine Acceleration

Effect of altitude and flight Mach number. - The third phase of a successful engine start is the acceleration of the engine rotor from the speed at which flame propagation was accomplished to normal operating speeds. At sea-level or low-altitude conditions the margin of turbine power for rapid acceleration is designed into the engine. At high altitude, where the compressor-inlet-air density may be as low as one-tenth that at sea level, the turbine power will have decreased by about the same ratio; while at the same time the inertia of the rotor masses to be accelerated has not changed. A large increase in the time required to accelerate the engine to a normal operating speed may then be expected.

Figure 19 indicates that there is a rapid increase in time required to accelerate the engine to 75 percent of maximum speed as altitude is increased. For example, at 0.6 flight Mach number the time required for acceleration increases from 1.1 to 6 minutes as altitude is increased from 45,000 feet to 54,000 feet.

Increased flight Mach number, however, has a very favorable effect on acceleration. With the higher pressure ratio across the engine at high flight Mach numbers, the initial or engine windmilling speed is much greater and requires a smaller speed increase in the acceleration phase of the start. At an altitude of 47,000 feet (fig. 19), the time required for acceleration was reduced from 5 minutes to 0.9 minute as flight Mach number was increased from 0.4 to 0.8. Time required for acceleration at altitude can then be reduced by diving the airplane to increase flight Mach number.

Effect of variable-area nozzle. - The time required for engine acceleration at high altitudes is extremely long, and requiring the pilot to dive the aircraft to reduce engine acceleration time is often impracticable. Since it appears impracticable to reduce greatly the inertia of the engine rotor, the only simple method of reducing acceleration time is to increase the power obtainable from the turbine. Since turbine-inlet gas temperatures cannot be increased because of material limitations, it is necessary to increase the pressure drop across the turbine by means of a variable-area jet nozzle. The effect of increasing the jet-nozzle area 40 percent is shown in figure 20. At an altitude of 47,000 feet and a flight Mach number of 0.4, the acceleration time was reduced from 5.0 to 3.0 minutes, a reduction of 40 percent. Even this reduction is insufficient for combat aircraft; and other methods of assisting the engine acceleration, such as adjustable turbine-nozzle blades to increase turbine power at very low engine speeds, should be explored.

Over-All Improvements in Altitude-Starting Limit

The improvements in altitude-starting limits made possible by some of the techniques discussed in this paper will be demonstrated by comparison of the standard engine and final configuration altitude-starting limits. A comparison of standard and final engine configurations is presented in the following table:

Item	Standard engine equipment	Final engine equipment
Type of ignition	Induction	Capacitance
Peak voltage, volts	15,000	10,000
Sparks per second	800	7
Joules per spark	0.02	3.7 (at spark gap)
Spark plugs	Champion F-19	Opposed electrodes
Spark-gap location	3/4 in. inside combustor	Center of combustor
Fuel nozzles	Duplex	Simplex (5 gal/hr tips)
Cross-fire-tube diameter	7/8 in.	2 in.
Jet nozzle	Fixed	Variable

The range of altitudes and flight Mach numbers over which altitude starts could be obtained is shown in figure 21 by the area shaded with the parallel lines, while the large gains in altitude starting obtained by these alterations are represented by the cross-hatched area. A maximum time of 1 minute was selected (as in fig. 6) as the basis for the altitude-acceleration limit. At a flight Mach number of 0.4 the acceleration limit was plotted for the engine with the jet area increased by 40 percent, which indicated an additional 7000-foot-altitude improvement as compared with the original jet-nozzle area. The flame-propagation limits are not indicated for the altered configuration, because altitude starting was limited only by ignition and acceleration. Flame propagation was obtained at all altitudes at which ignition could be achieved. However, high-altitude flame propagation could not be achieved with the fuel flow required for ignition but required momentary throttling to a lower fuel flow. Finally, the data of figure 21 show that the configuration changes produced appreciable gains in the altitude-starting limit. At 0.6 flight Mach number the starting limit was increased from 15,000 to 43,000 feet, a gain of 28,000 feet; while at a flight Mach number of 0.8 the altitude-starting limit was increased from about sea level to 47,000 feet.

CONCLUDING REMARKS

The present investigation shows methods of improving the altitude-starting limits of a turbojet engine. At a flight Mach number of 0.6 the altitude-starting limit of the production-type turbojet engine was increased from 15,000 to 43,000 feet, and at a flight Mach number of 0.8 the altitude limit was increased from about sea level to 47,000 feet. The improvements in altitude-starting limit required improvement in all three phases of the engine start: (1) ignition of the combustors containing spark plugs, (2) propagation of flame through the cross-fire tubes to ignite the remaining combustors, and (3) acceleration from windmilling speed to a useful rotor speed.

Of the many variables investigated, increasing the spark energy at the spark gap provided the greatest gain in altitude-ignition limit. Replacing the engine ignition system which provided 0.02 joule per spark and 800 sparks per second with a high-energy capacitance-type ignition system providing 3.7 joules per spark at 7 sparks per second increased the altitude-ignition limit from 15,000 to 53,000 feet at 0.6 flight Mach number and from sea level to 47,000 feet at 0.8 flight Mach number. In order to obtain a high energy at the spark gap, it was necessary to replace the standard ignition harness and connectors with a low-resistance cable and low-resistance connection to the spark plugs. It appears that emphasis on low-resistance ignition cables, on low-resistance positive contact connectors, and on care to keep corona losses to a minimum is essential if the high energy from a capacitance discharge system is to reach and be dissipated at the spark-plug gap.

The propagation of flame from combustors having spark plugs to the remaining combustors was limited in the original engine to altitudes to 30,000 feet. An increase in the cross-fire-tube diameter from 7/8 to 2 inches improved the flame-propagation ability to the extent that propagation could be obtained at any altitude at which ignition could be obtained. Throttle manipulation, however, was an important factor in obtaining high-altitude flame propagation.

Acceleration of the engine at high altitude without exceeding limiting turbine-outlet temperatures required excessive time intervals. At 47,000 feet and a flight Mach number of 0.4, 5.0 minutes was required to accelerate the engine from windmilling speed to 75 percent of maximum speed. The use of a variable-area jet nozzle to increase the nozzle area 40 percent during acceleration decreased the time required for acceleration from the 5.0-minute interval to 3.0 minutes, a reduction of 40 percent.

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TABLE I - EXPERIMENTAL VARIABLES

Variable investigated	Fuel nozzle	Throttle control	Fuel	Ignition system	Spark plugs	Flight conditions	
						Altitude (ft)	Mach number
Ignition							
Fuel volatility	Variable-area	Varied	MIL-F-5624 and 1 lb Reid vapor pressure	Induction - 800 sparks/sec 0.02 j/spark	Standard A.C. F-67	Sea level-50,000	0.2-0.8
Fuel and air temperatures	Variable-area	Varied	1 lb Reid vapor pressure	Induction - 800 sparks/sec 0.02 j/spark	Standard A.C. F-67	10,000 - 35,000	0.6
Spark-gap immersion into combustor	Variable-area	Varied	1 lb Reid vapor pressure	Induction - 800 sparks/sec 0.02 j/spark	A.C. F-67 with lengthened electrodes	Sea level-40,000	0.2-0.8
Spark energy	Simplex, 5 gal/hr tips	Varied	1 lb Reid vapor pressure	High-energy capacitance	Opposed electrodes	35,000 - 55,000	0.6
Spark-repetition rate and power required for ignition	Simplex, 5 gal/hr tips	Fixed	1 lb Reid vapor pressure	High-energy capacitance	Opposed electrodes	50,000	0.6
Comparison of two capacitance-type units with different voltages	Simplex, 5 gal/hr tips	Fixed	1 lb Reid vapor pressure	High-energy units: 10,000 v spark and 1,000 v spark	Opposed electrodes Standard A.C. F-19	35,000 - 50,000	0.6
Flight Mach number	Simplex, 5 gal/hr tips	Fixed	1 lb Reid vapor pressure	High-energy capacitance 10,000 v	Opposed electrodes	46,000 - 57,000	0.4-1.2
Flame propagation							
Cross-fire-tube diameter (0.875 to 2.0 in.)	Variable-area	Varied	1 lb Reid vapor pressure	High-energy capacitance 10,000 v	Opposed electrodes	30,000 - 50,000	0.2-1.0
Cross-fire-tube location	Variable-area	Varied	1 lb Reid vapor pressure	High-energy capacitance 10,000 v	Opposed electrodes	42,500 - 55,000	0.4-1.0
Fuel volatility	Variable-area	Varied	MIL-F-5624 and 1 lb Reid vapor pressure	Induction - 800 sparks/sec 0.02 j/spark	Standard A.C. F-67	30,000 - 40,000	0.4-0.8
Fuel atomization characteristics	Variable-area Simplex Duplex	Varied	1 lb Reid vapor pressure	High-energy capacitance 10,000 v	Standard A.C. F-67	45,000 - 50,000	0.4-1.0
Engine acceleration							
Flight Mach number and altitude	Simplex, 5 gal/hr tips	Varied	1 lb Reid vapor pressure	High-energy capacitance 10,000 v	Opposed electrodes	35,000 - 54,000	0.2-0.8
Variable-area exhaust nozzle	Simplex, 5 gal/hr tips	Varied	1 lb Reid vapor pressure	High-energy capacitance 10,000 v	Opposed electrodes	35,000 - 50,000	0.4

TABLE II - FUEL INSPECTION DATA

ASTM distillation D 86-46, °F	Experimental 1 pound Reid vapor pressure	MIL-F-5624 Grade JP-3
Initial boiling point	181	124
Percent evaporated		
5	242	156
10	271	180
20	300	220
30	319	252
40	332	282
50	351	312
60	365	344
70	381	378
80	403	408
90	441	447
Final boiling point	508	498
Residue, percent	1.0	1.0
Loss, percent	0.5	0.5
Freezing point, °F	-76	-76
Accelerated gum, mg/100 ml	5	------
Air jet residue, mg/100 ml	2	------
Aromatics, percent by volume, silica gel	5.70	------
Specific gravity	0.780	0.760
Bromine number	1.4	------
Reid vapor pressure, lb/sq in.	1.0	6.2
Hydrogen-carbon ratio	0.170	0.171
Net heat of combustion, Btu/lb	18,690	18,720

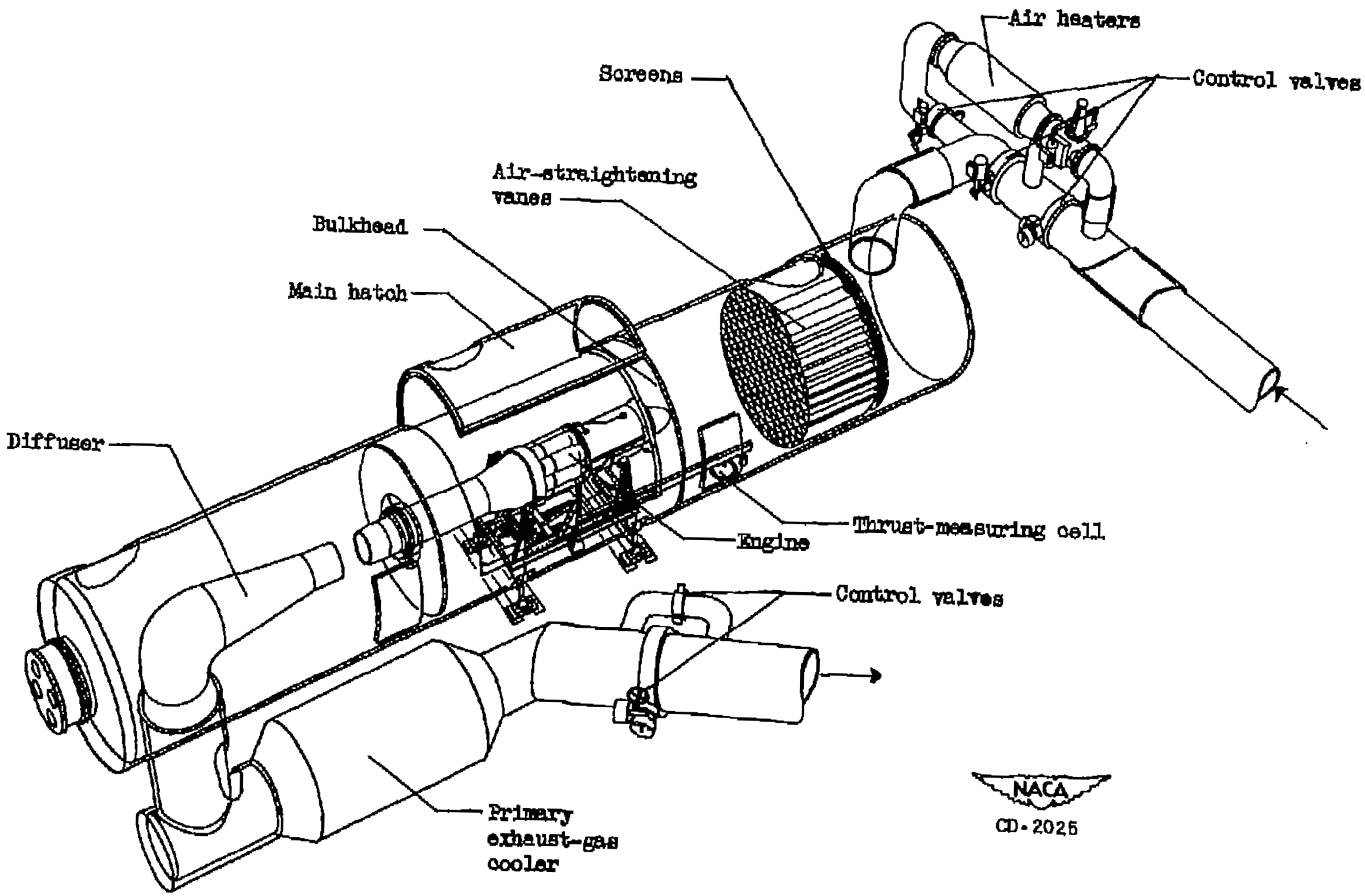


Figure 1. - Altitude chamber with engine installed.

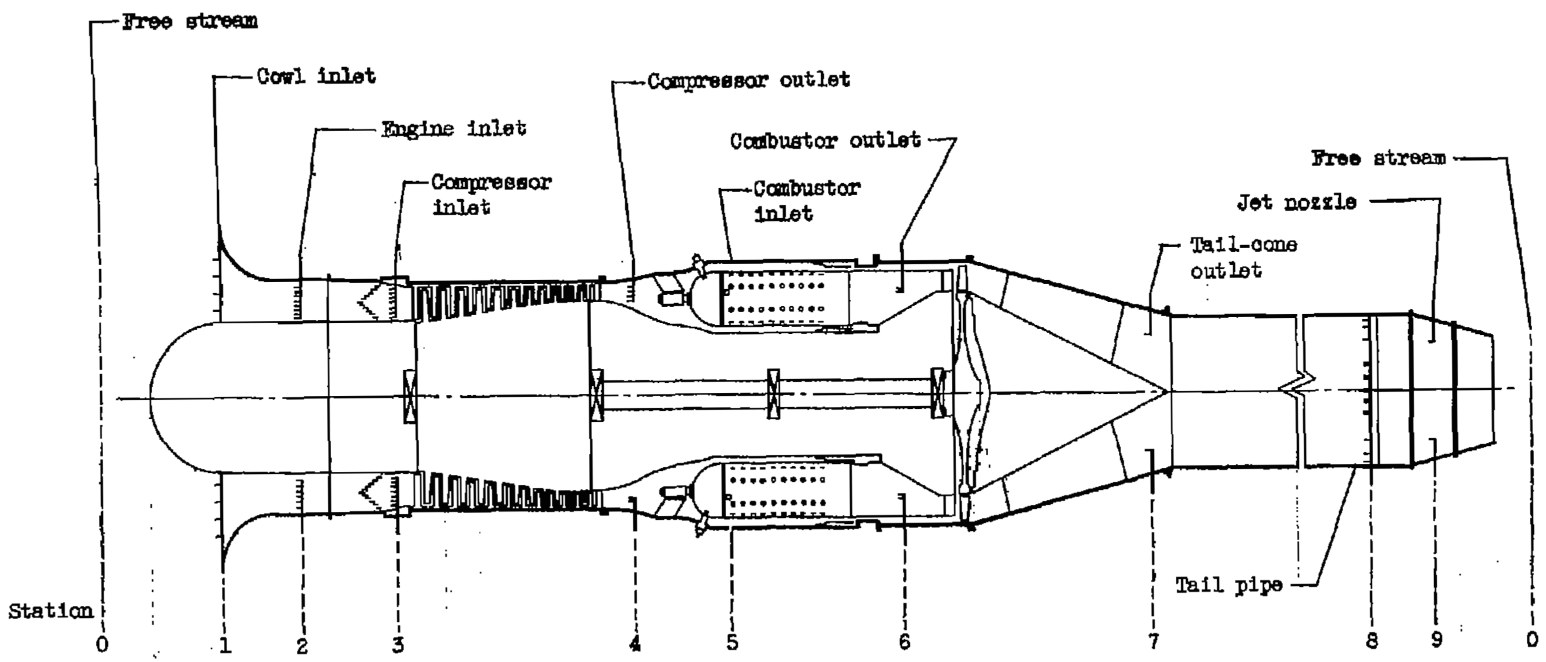


Figure 2. - Engine instrumentation stations.

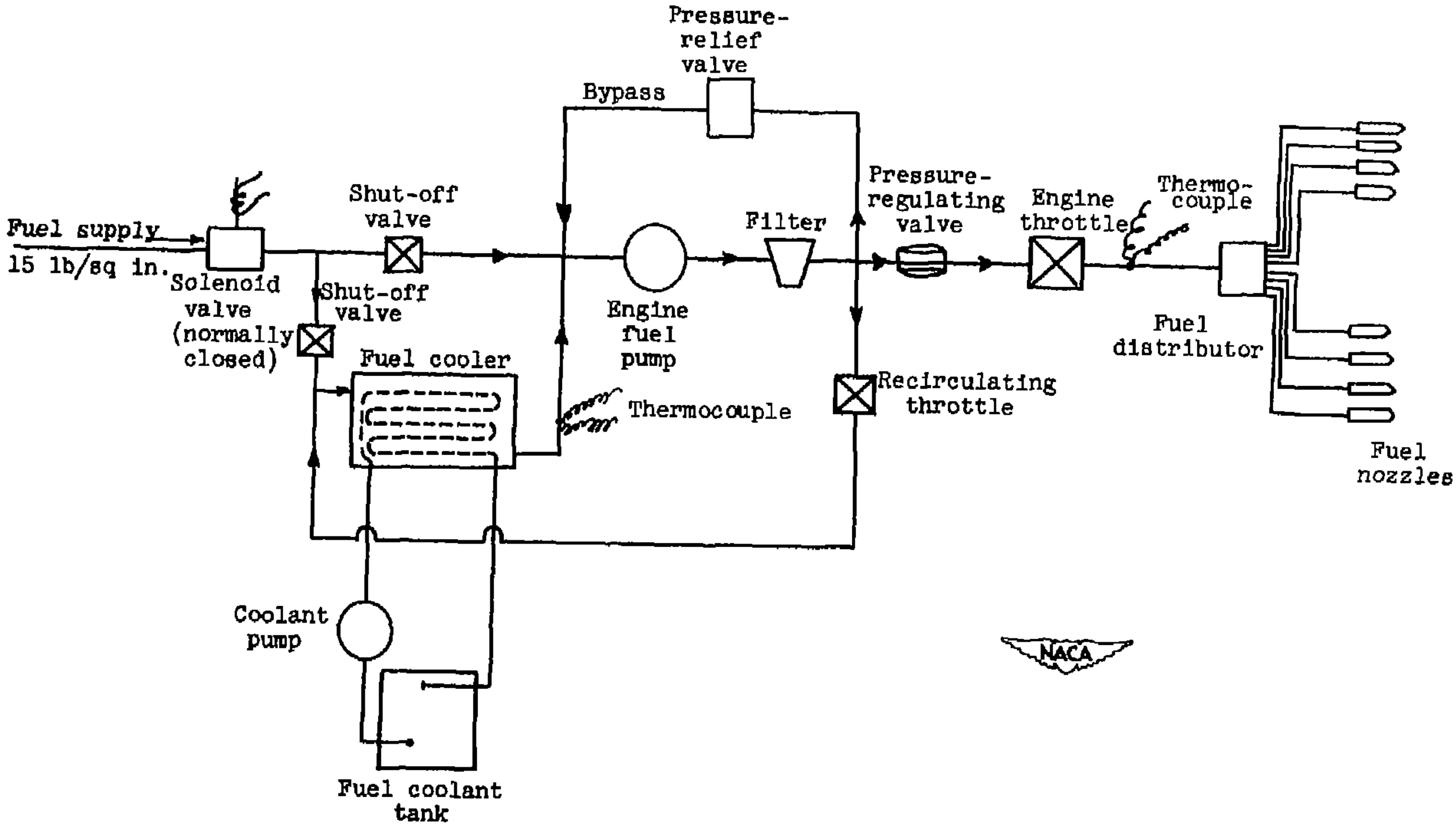
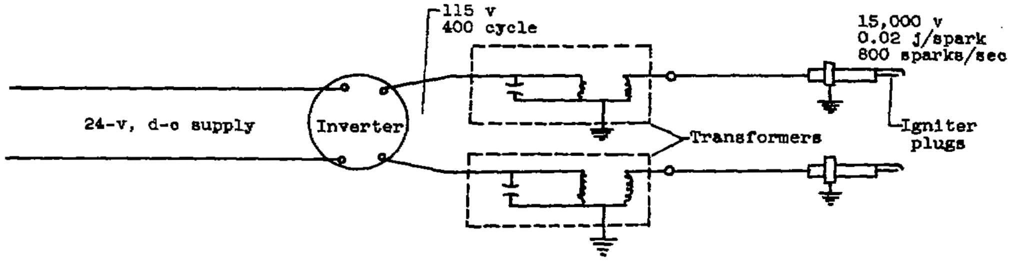
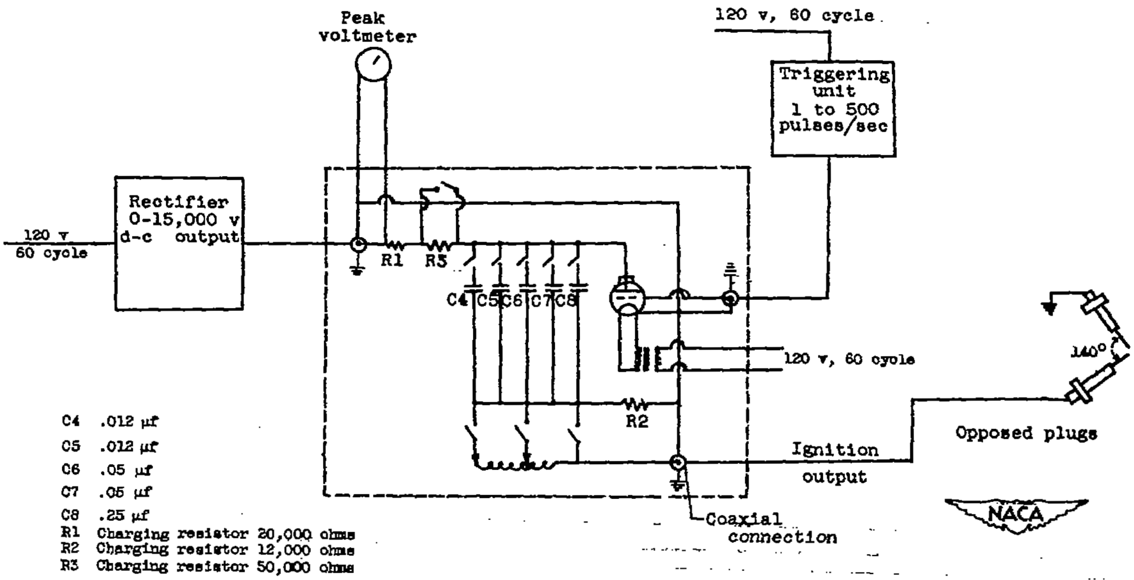


Figure 3. - Schematic diagram of fuel system.

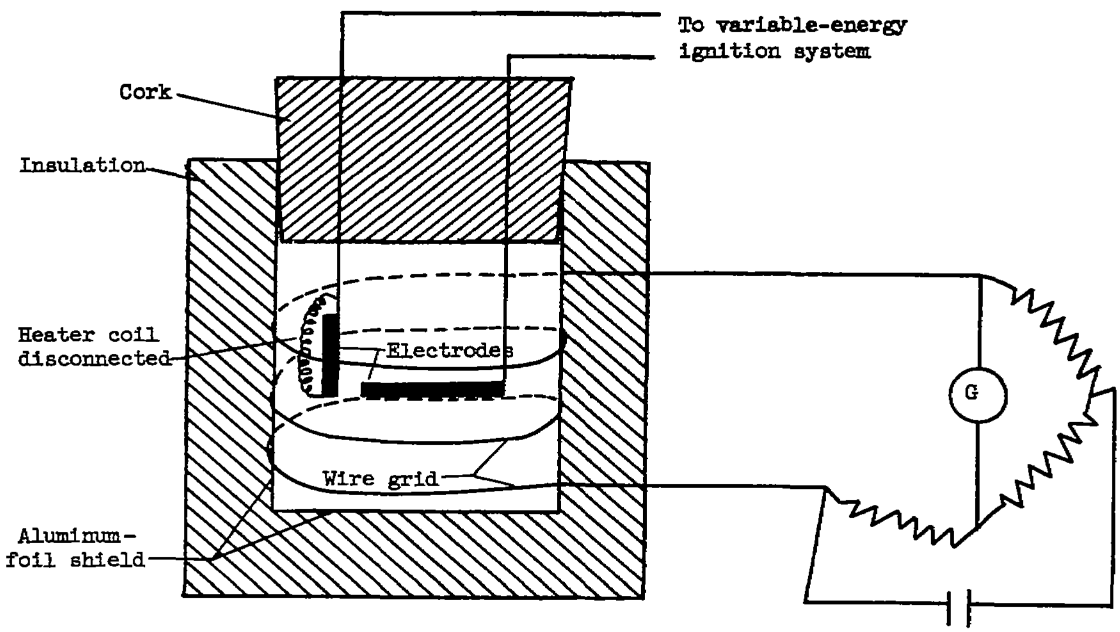


(a) Standard induction-type ignition system.

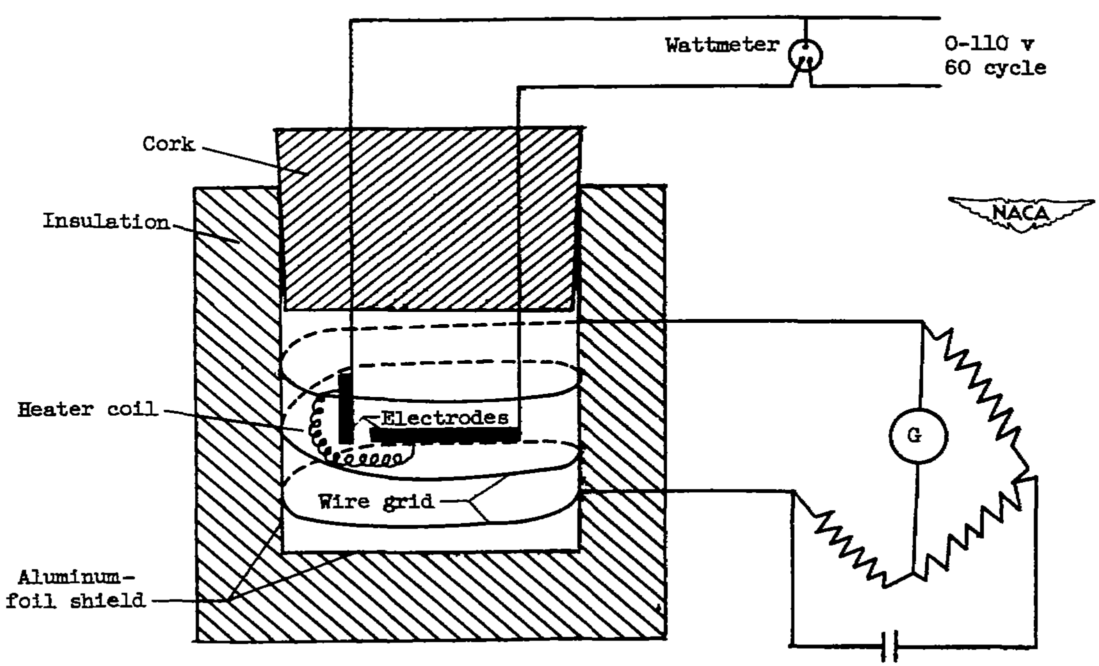


(b) High-energy variable-sparking-rate capacitance-type ignition system.

Figure 4. - Schematic diagram of ignition systems.



(a) Setup to determine grid-resistance change of various spark outputs.



(b) Setup to calibrate grid-resistance change against heater-coil power consumption.

Figure 5. - Schematic diagram of system used to determine spark energy.

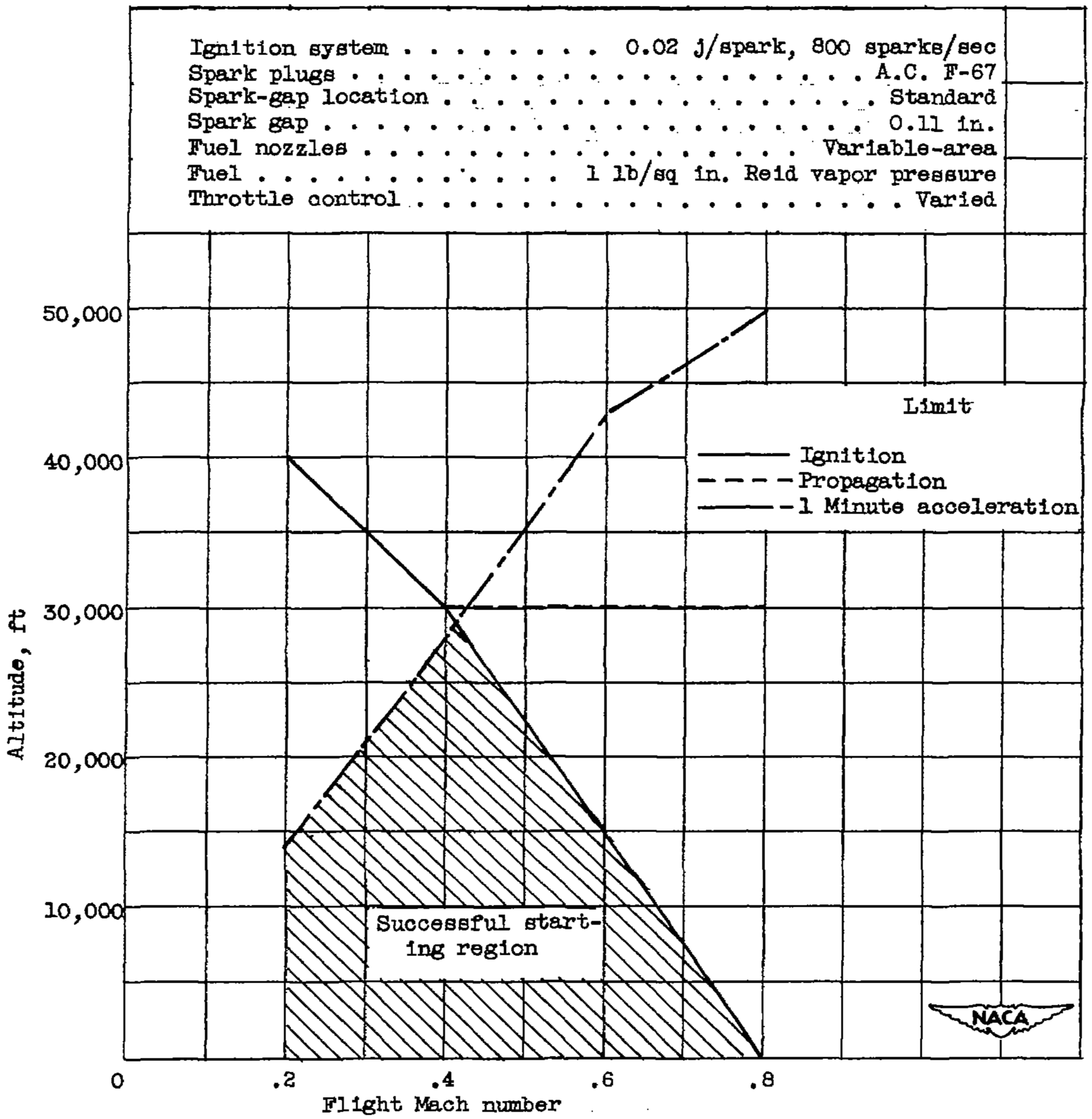


Figure 6. - Altitude-starting limits of standard turbojet engine.

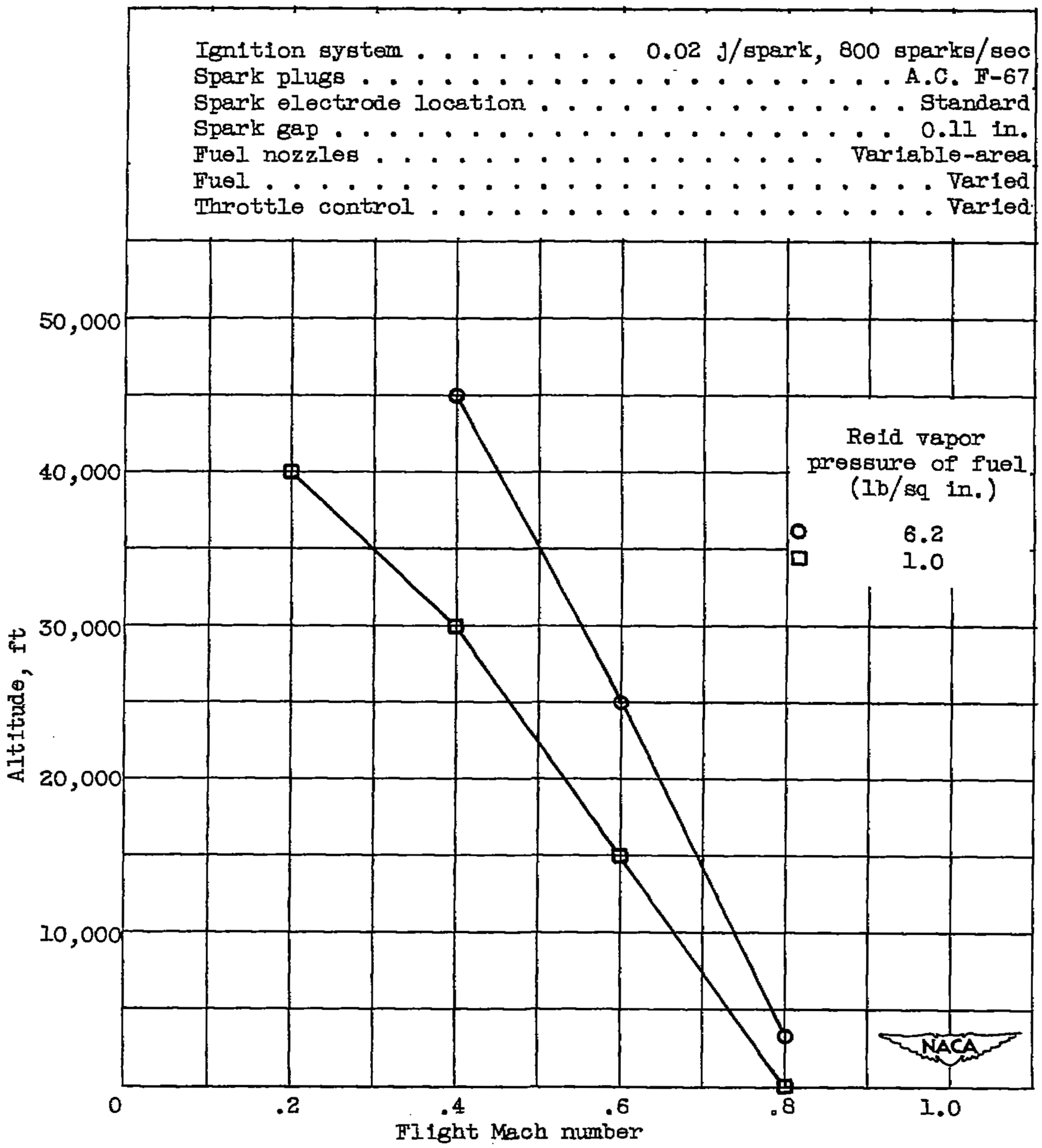


Figure 7. - Effect of fuel volatility on altitude-ignition limits of turbojet engine.

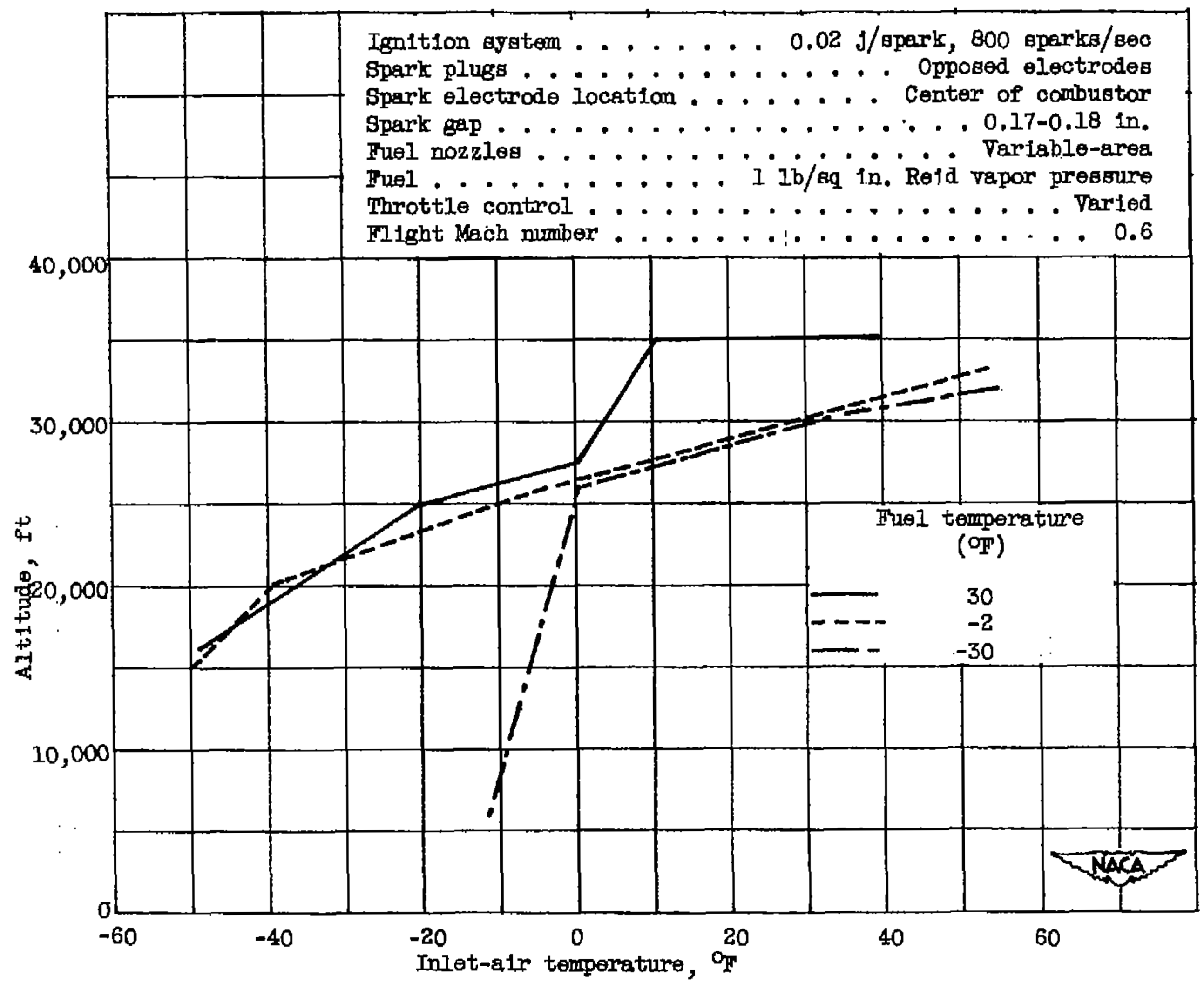


Figure 8. - Effect of engine inlet-air and fuel temperatures on altitude-ignition limits of turbojet engine.

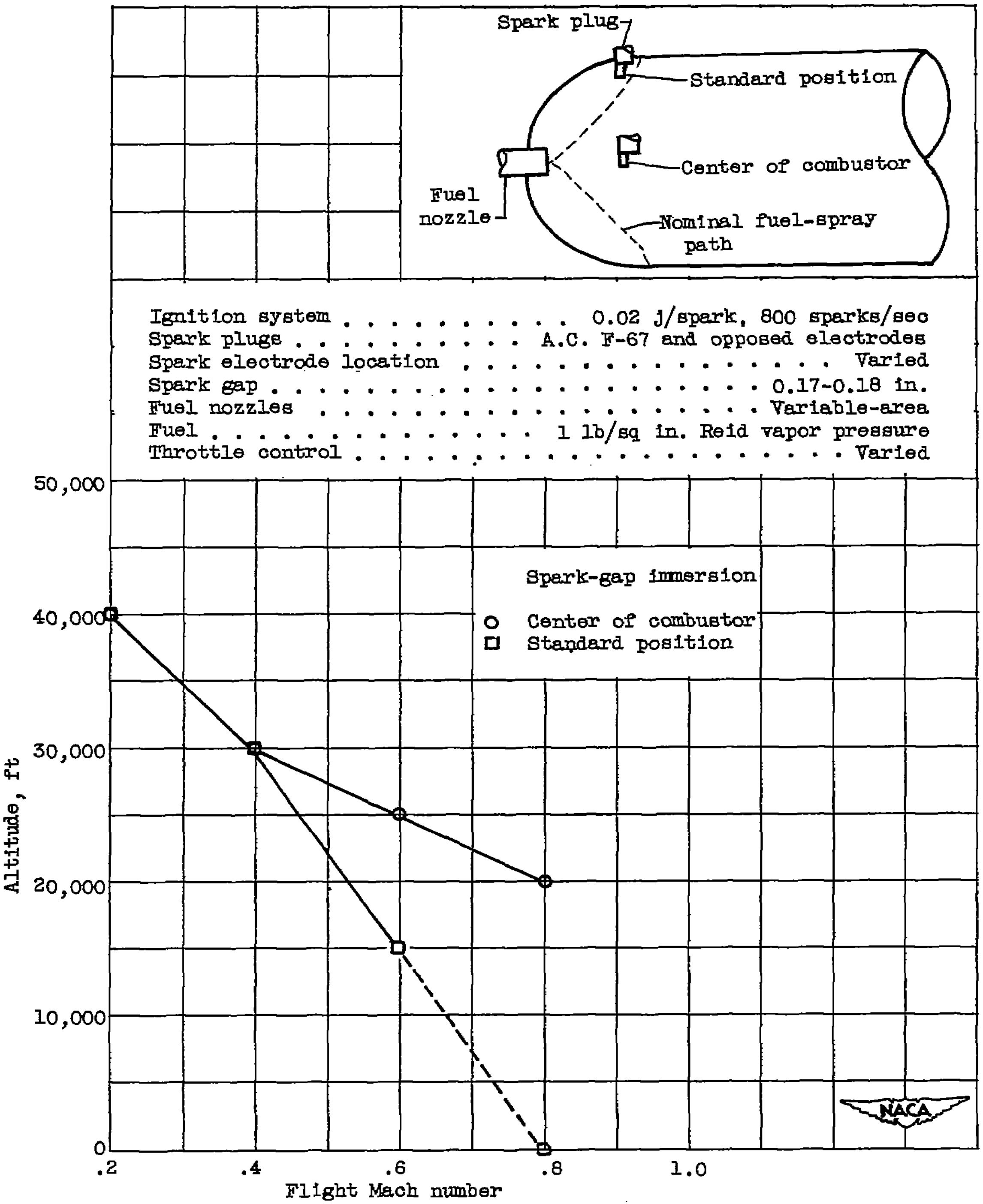


Figure 9. - Effect of spark-gap immersion on altitude-ignition limits of turbojet engine.

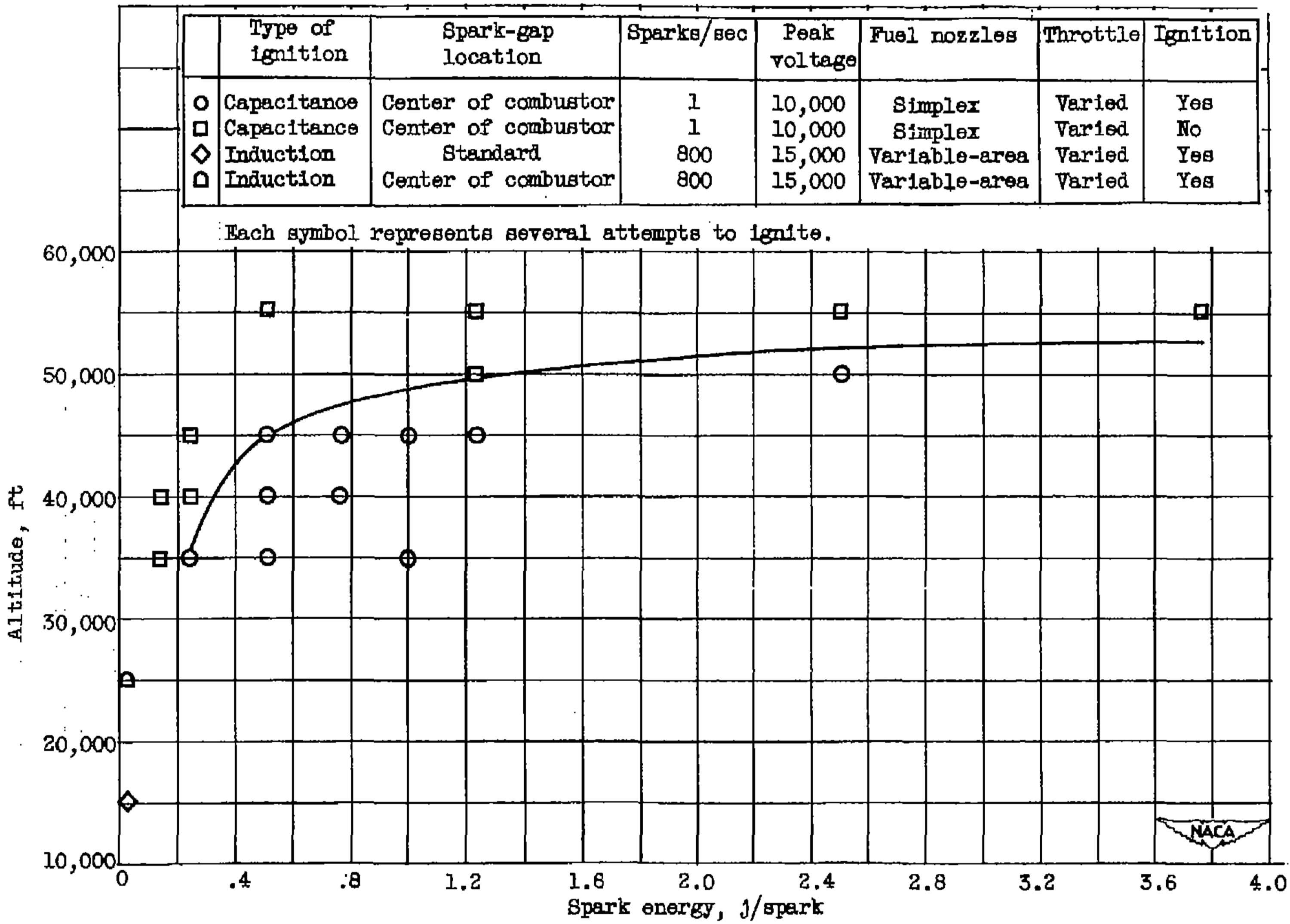
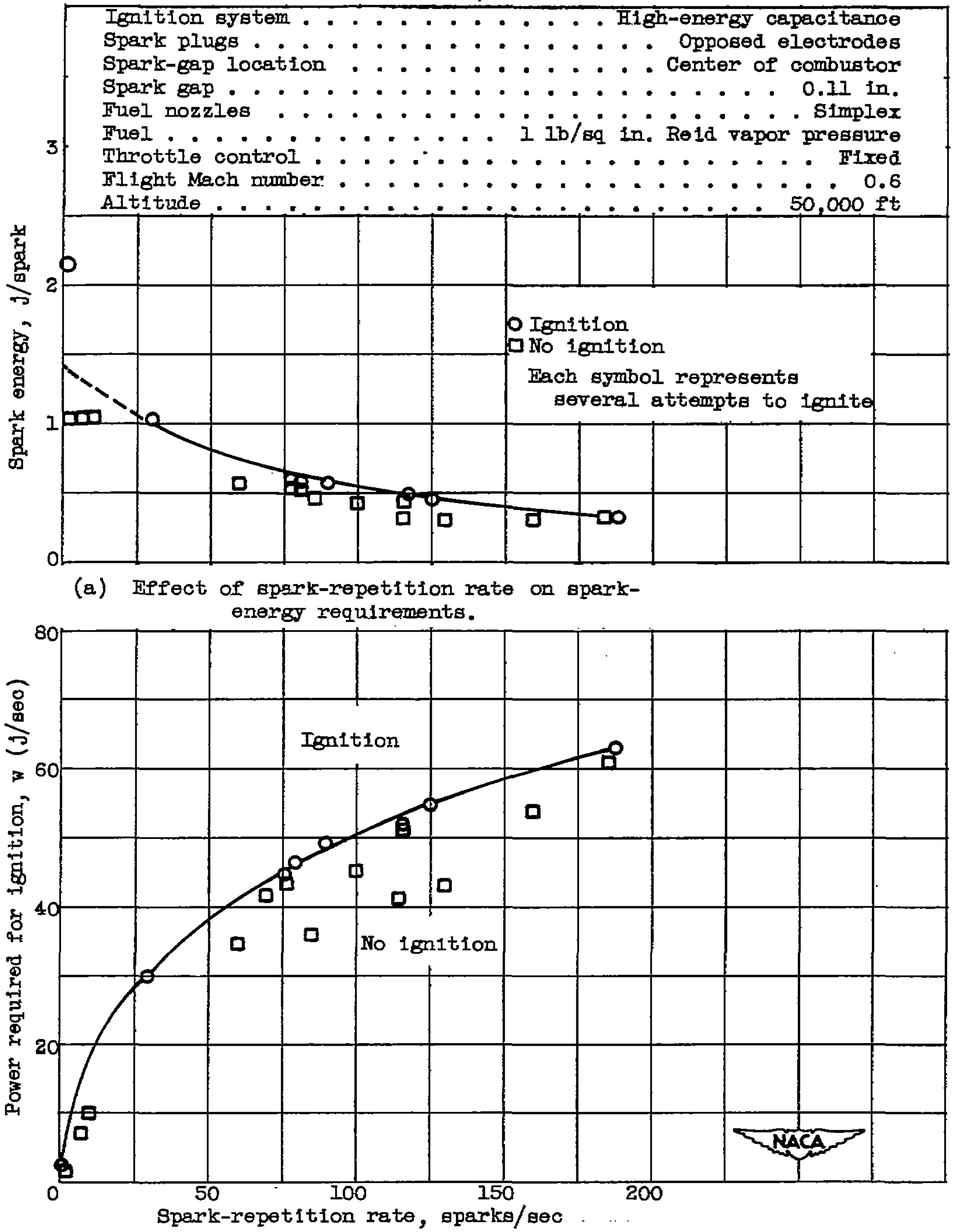


Figure 10. - Effect of spark energy on altitude-ignition limits at flight Mach number of 0.6.



(a) Effect of spark-repetition rate on spark-energy requirements.

(b) Power required for ignition at various spark energies.

Figure 11. - Spark energy and power required for ignition for various spark-repetition rates.

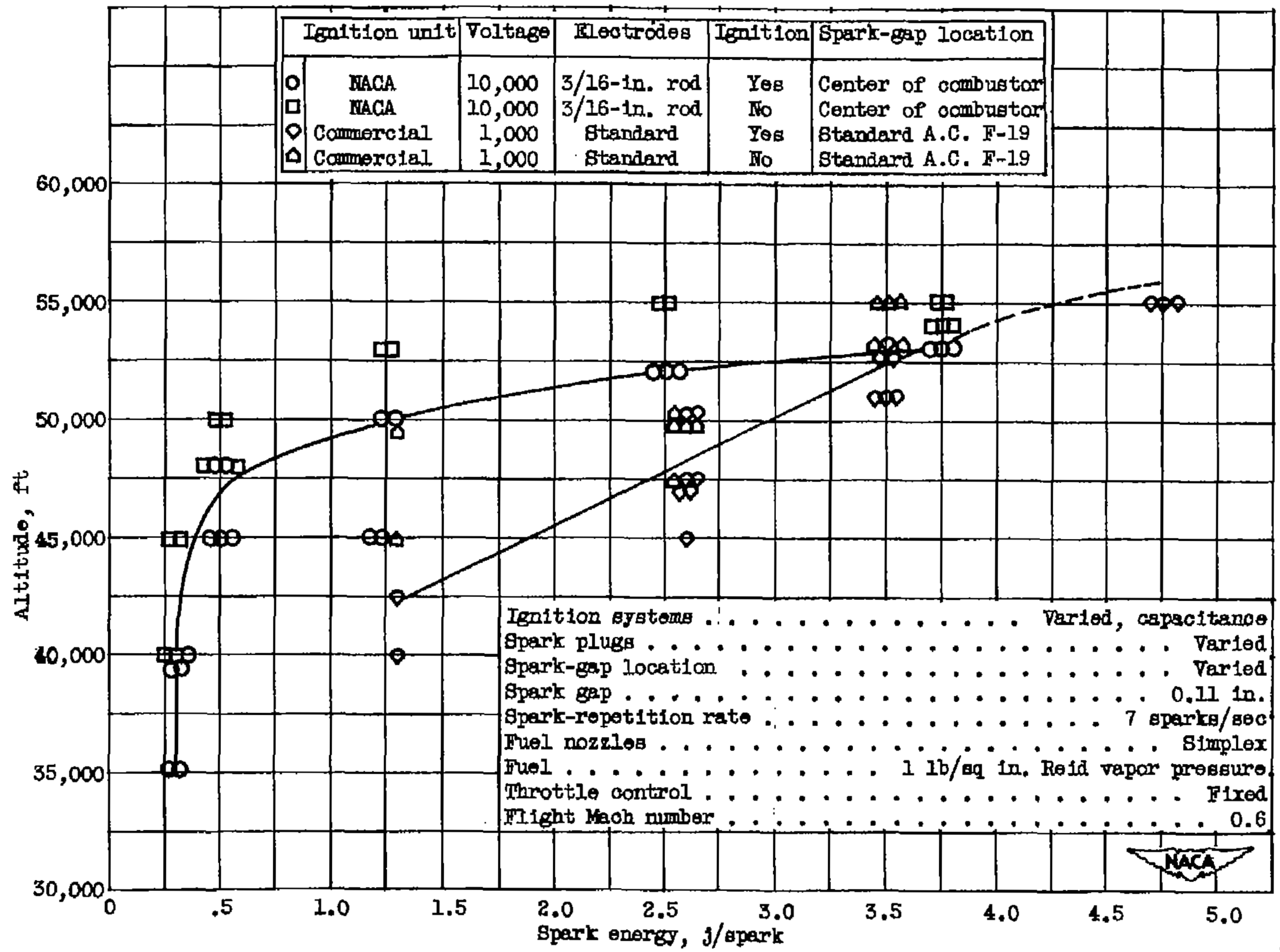


Figure 12. - Comparison of altitude-ignition limits of commercial development capacitance ignition unit and NACA capacitance unit.

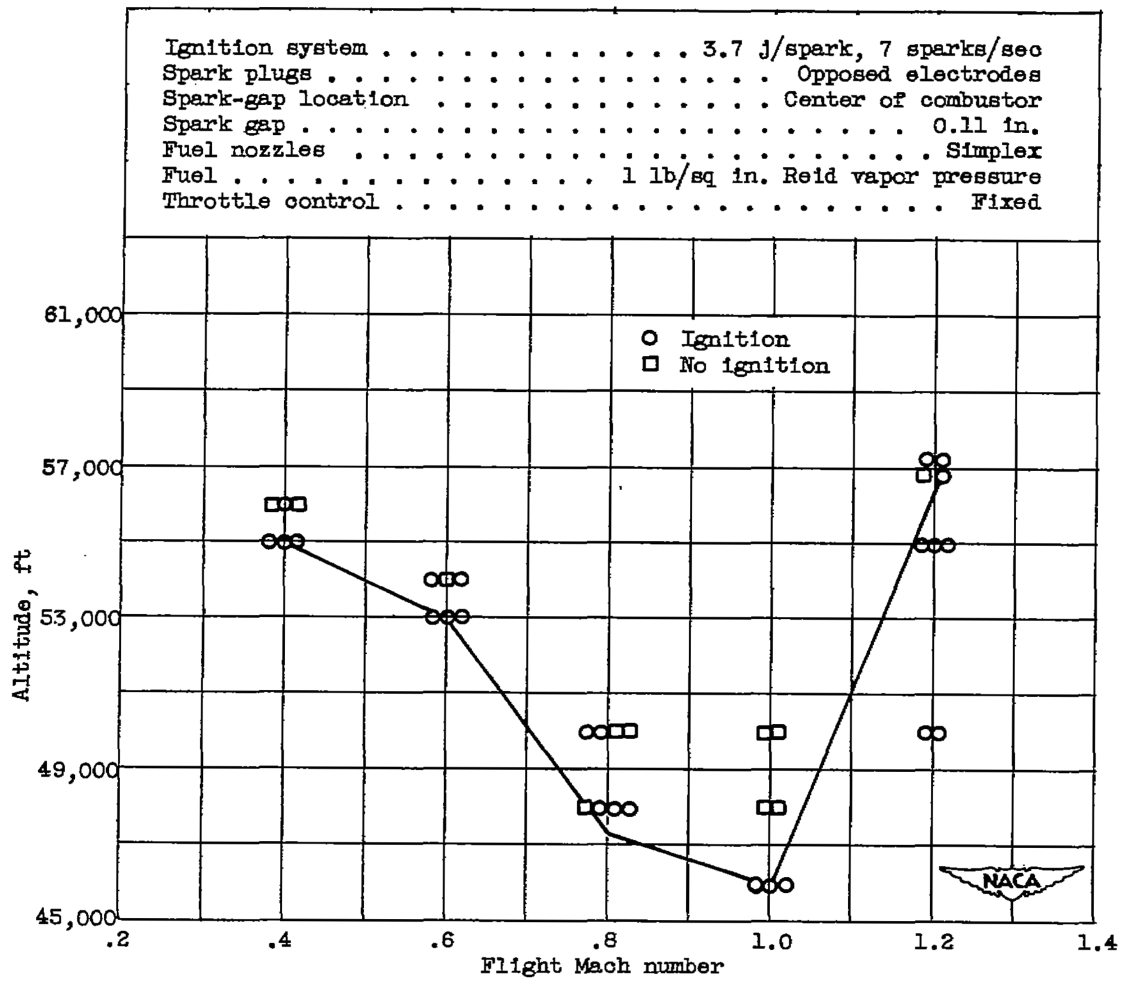


Figure 13. - Effect of flight Mach number on altitude-ignition limit of turbojet engine using 10,000-volt capacitance ignition unit.

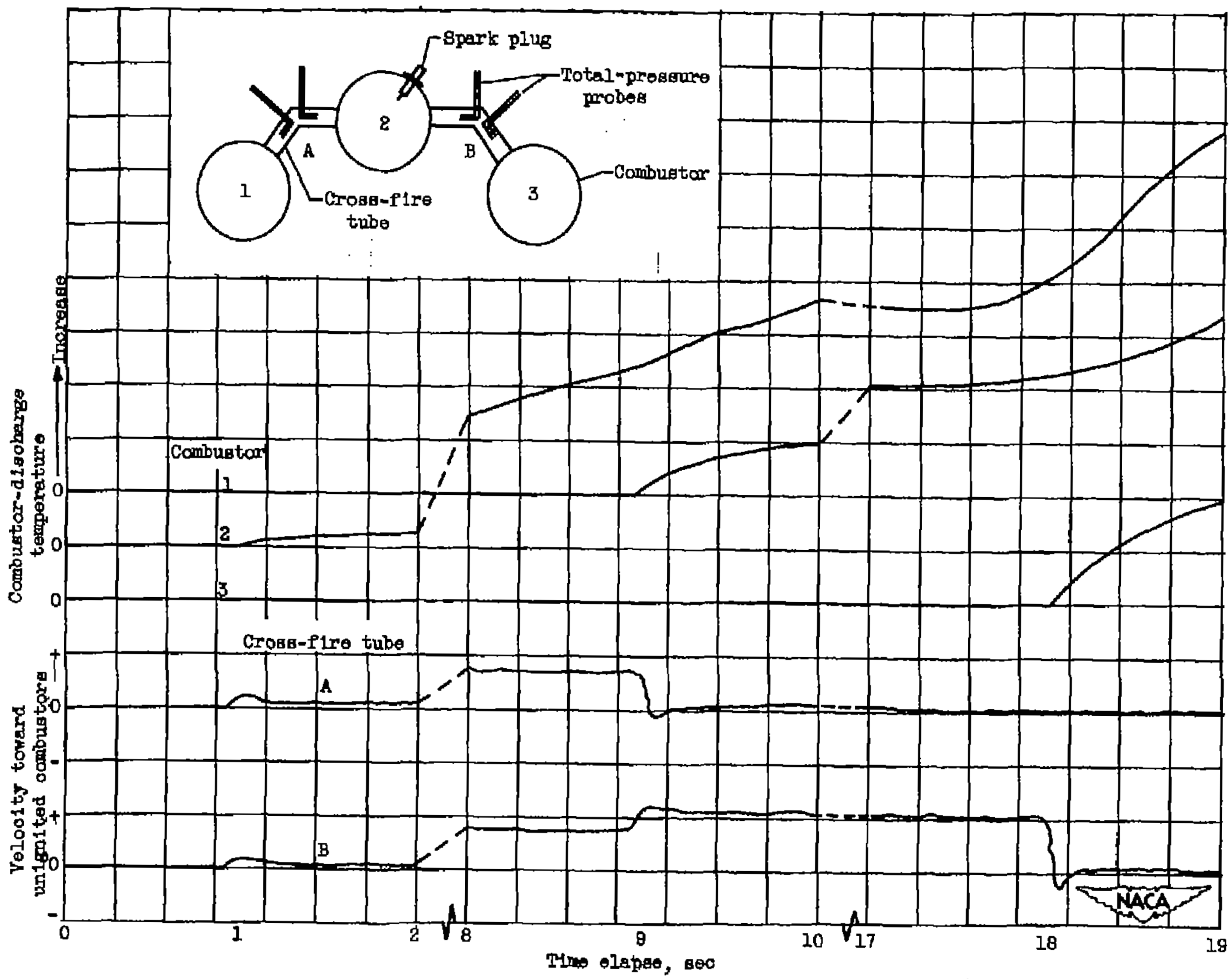


Figure 14. - Typical oscillograph trace showing velocity changes in cross-fire tubes during ignition and flame propagation at high altitude.

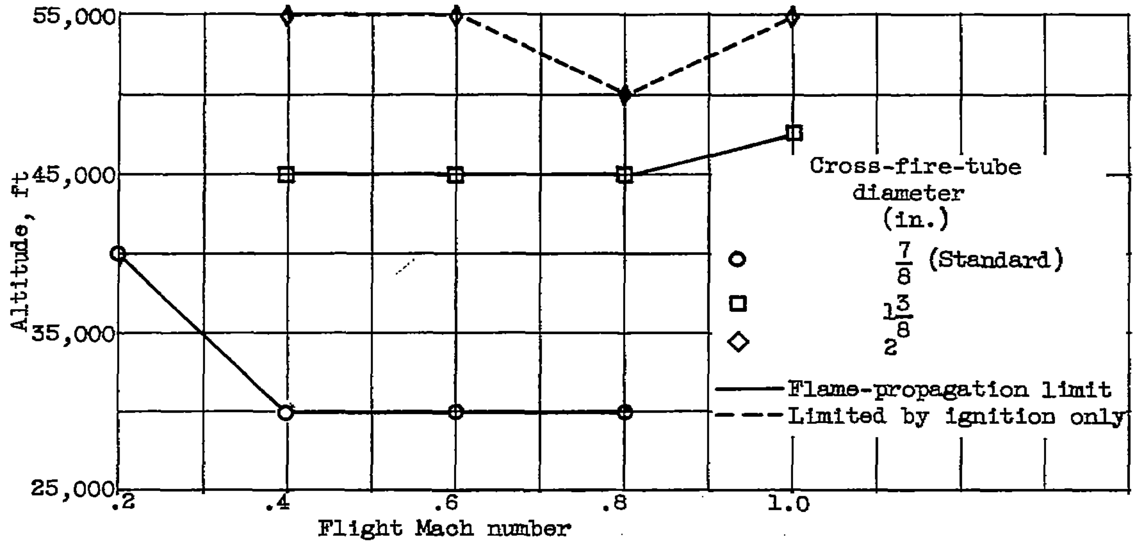


Figure 15. - Effect of cross-fire-tube diameter on flame-propagation limits of turbojet engine with variable-area fuel nozzles and standard cross-fire-tube location.

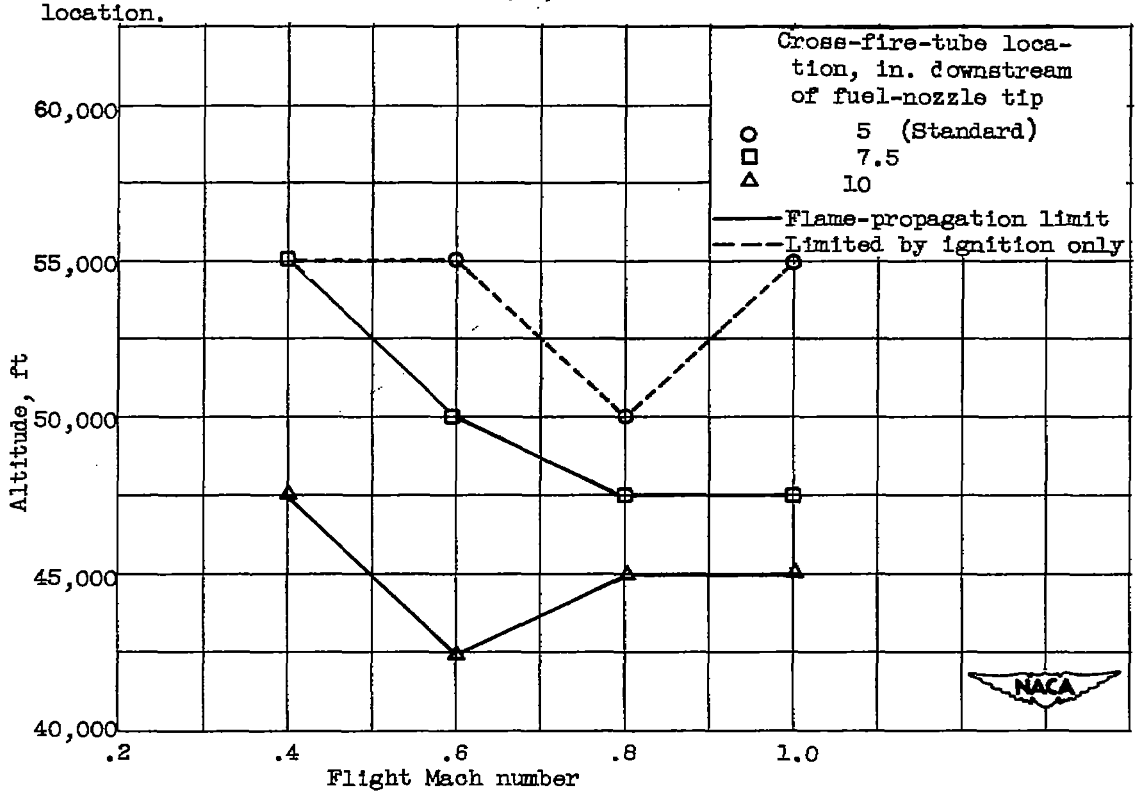


Figure 16. - Effect of cross-fire-tube location on flame-propagation limits of turbojet engine with 2-inch-diameter cross-fire tubes and variable-area fuel nozzles.

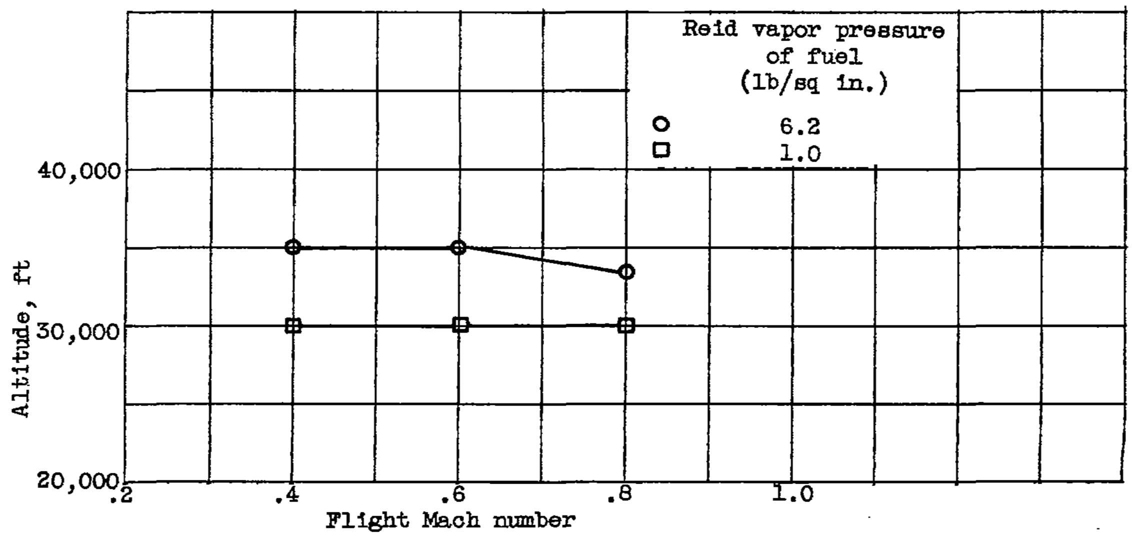


Figure 17. - Effect of fuel volatility on flame limits of turbojet engine. Cross-fire-tube diameter, 7/8 inch; standard engine location; variable-area fuel nozzles.

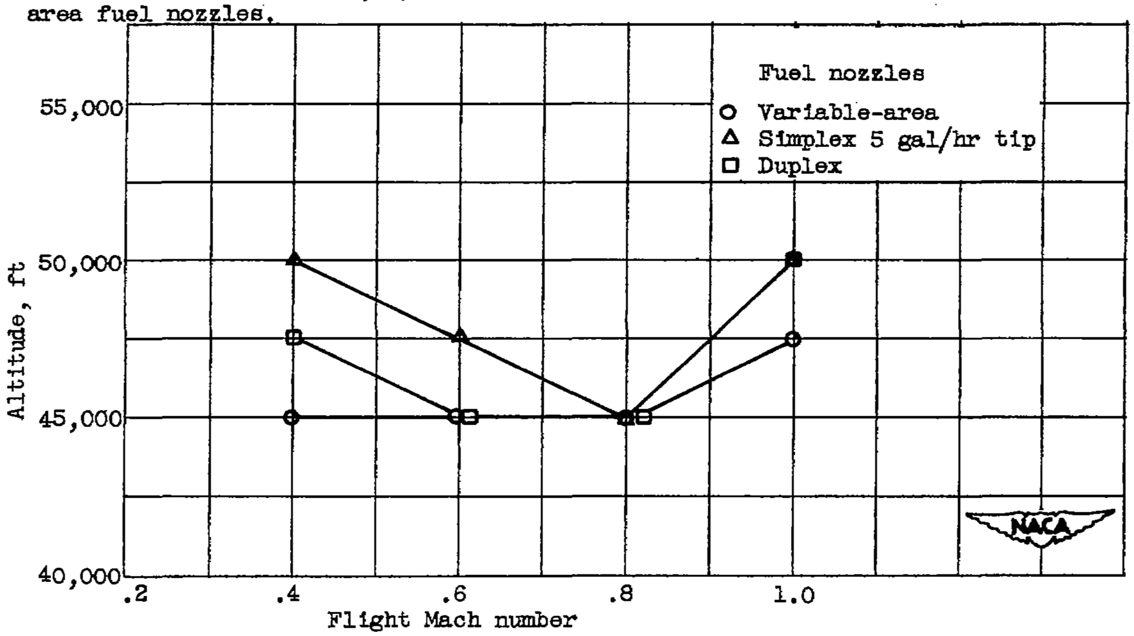


Figure 18. - Effect of three types of fuel nozzle on flame-propagation limits of turbojet engine with $1\frac{3}{8}$-inch-diameter cross-fire tubes in standard location.

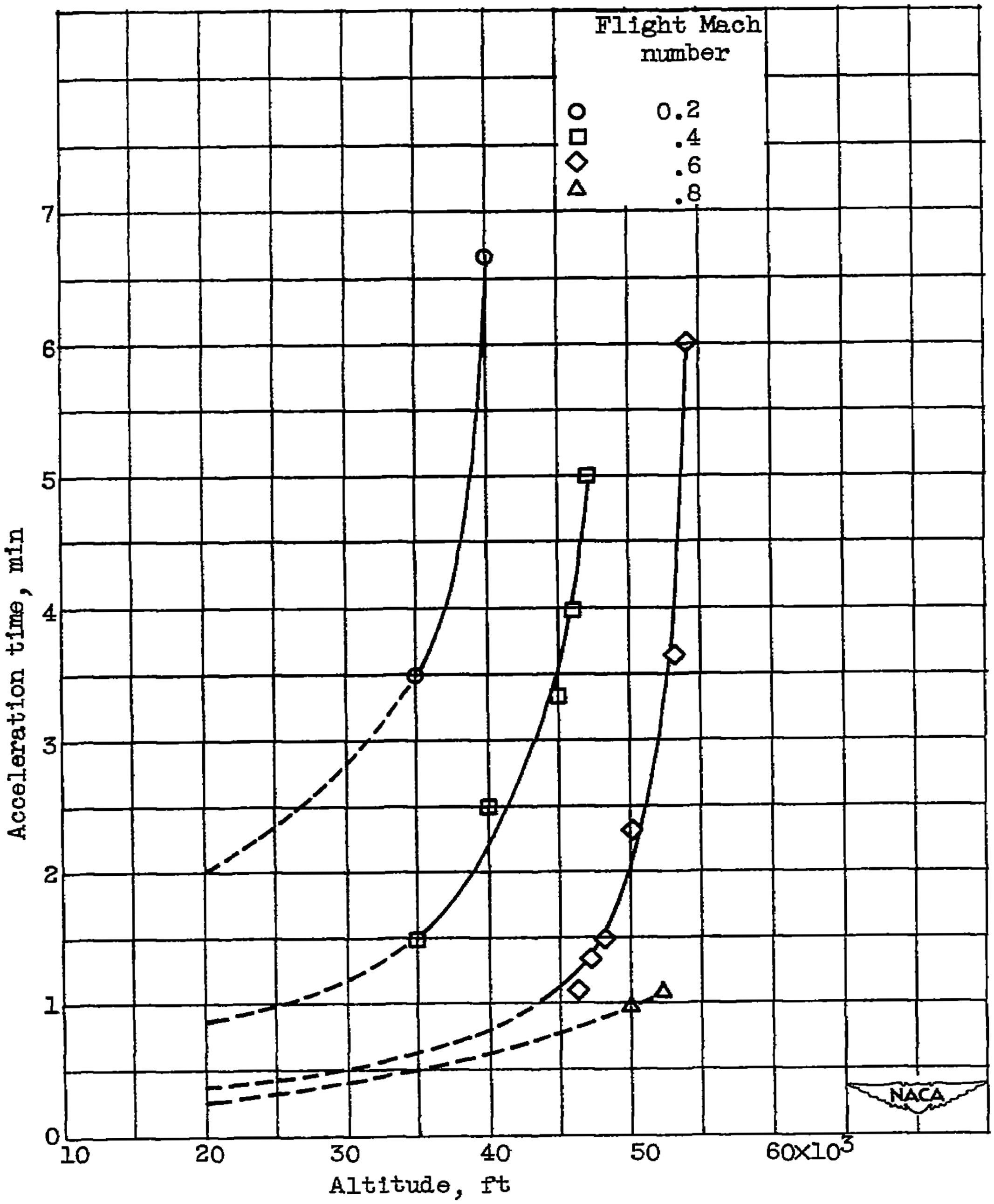


Figure 19. - Effect of altitude on time required to accelerate from windmilling to 75-percent rated engine speed at several flight Mach numbers. Maximum allowable turbine-outlet temperature, 1760° R.

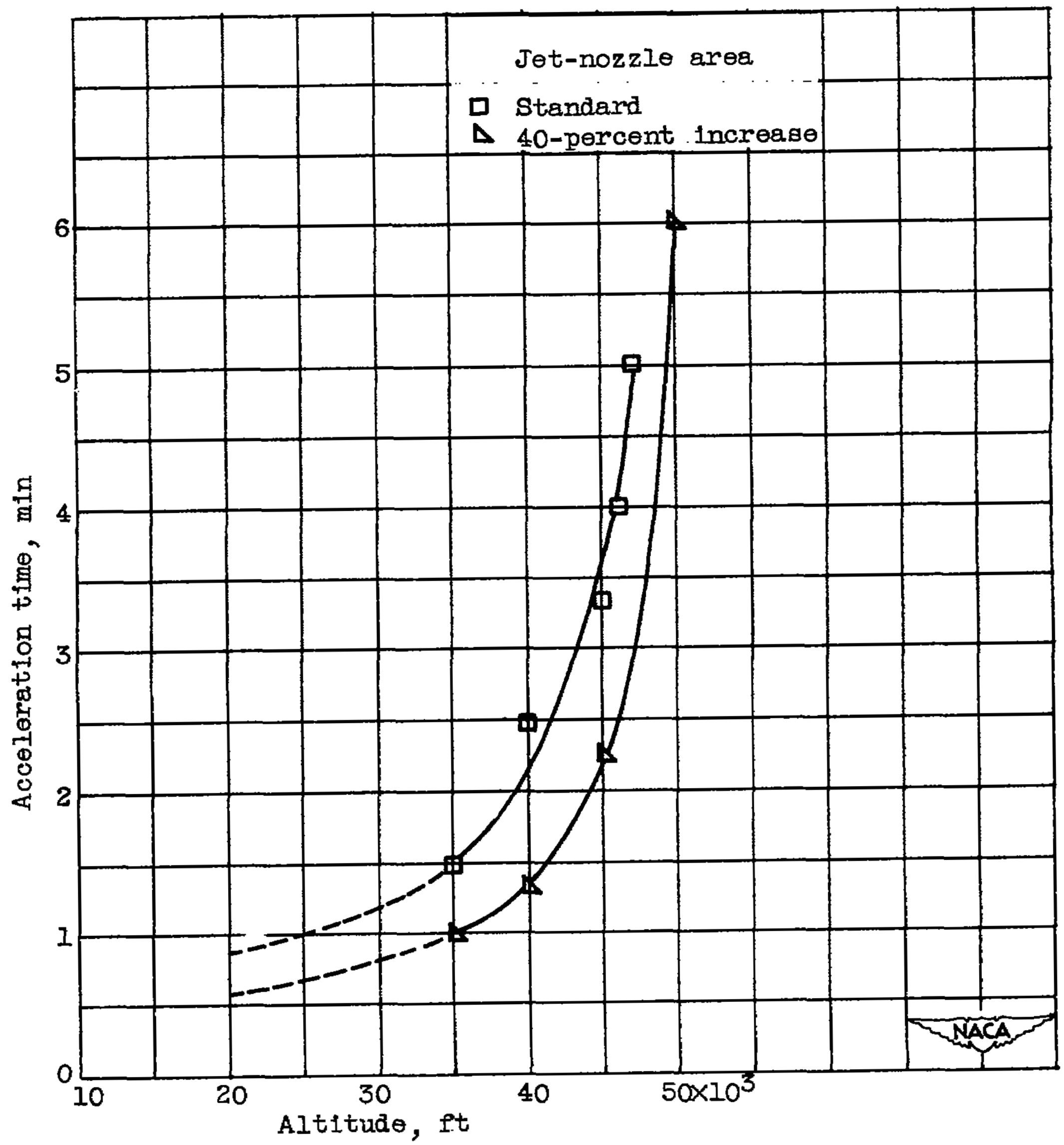


Figure 20. - Effect of jet-nozzle area on time required to accelerate from windmilling to 75-percent rated engine speed. Flight Mach number, 0.4; maximum allowable turbine-outlet temperature, 1760° R.

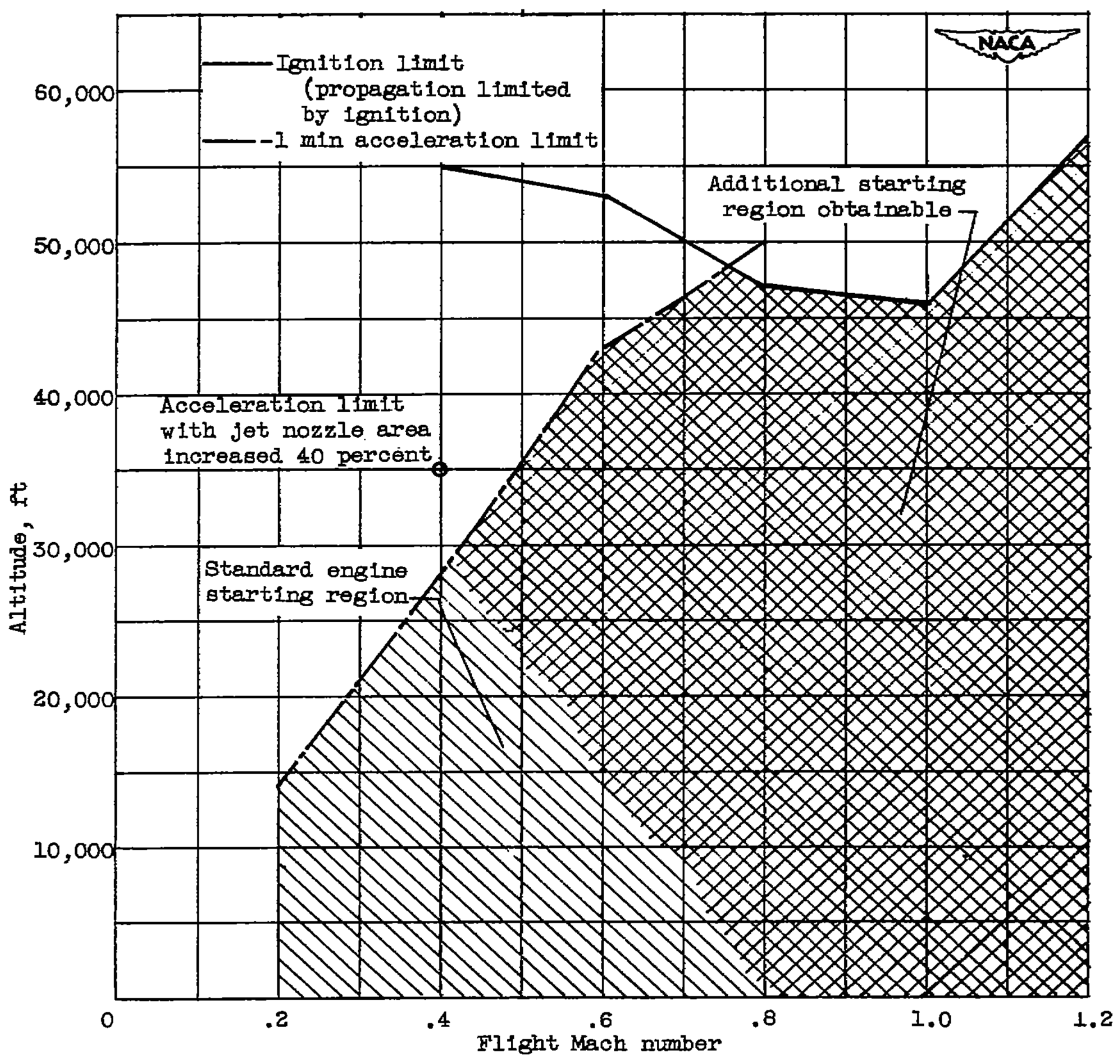


Figure 21. - Comparison of altitude-starting limits of turbojet engine before and after alterations of ignition system, cross-fire-tube diameter, and jet nozzle.